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Hashimoto et al.

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(54) **PLASMA LIGHT SOURCE AND INSPECTION APPARATUS INCLUDING THE SAME**

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H05G 2/00 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC **G01N 21/8806** (2013.01); **G01N 21/9501** (2013.01); **G01N 21/956** (2013.01); **G02B 21/06** (2013.01); **G02B 27/141** (2013.01); **G03F 7/70616** (2013.01); **H01J 61/025** (2013.01); **H01J 65/04** (2013.01); **H05G 2/008** (2013.01)

(58) **Field of Classification Search**

CPC G01N 21/8806; G01N 21/9501; G01N 21/956; G02B 21/06; G02B 27/141; G03F 7/2004; H01J 65/04; H01J 65/11
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,265,813 B1 7/2001 Knox et al.
7,368,741 B2 5/2008 Melnychuk et al.
(Continued)

FOREIGN PATENT DOCUMENTS

JP 2010-171219 8/2010
JP 2010-210717 9/2010
KR 1020130076982 7/2013

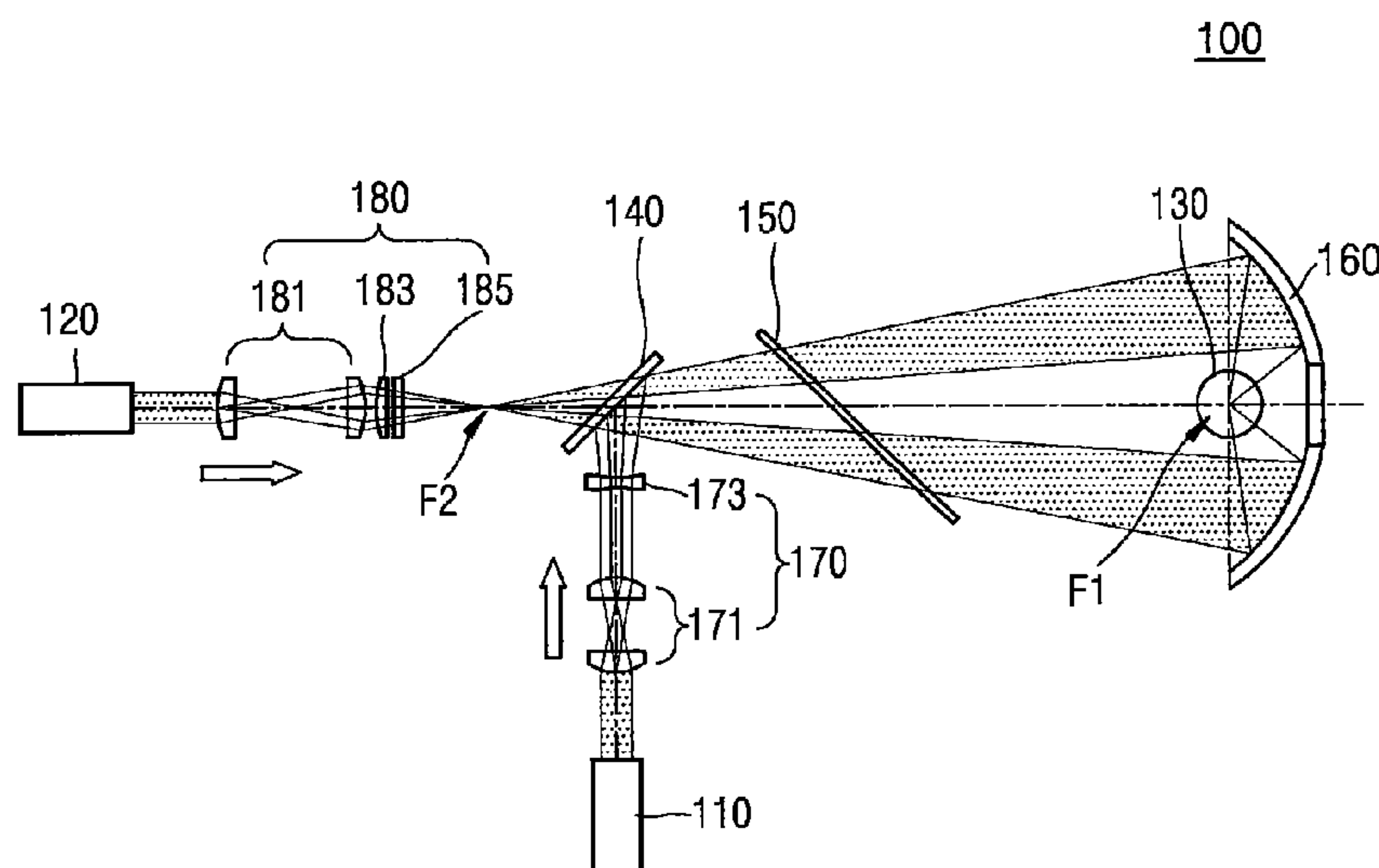
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(57) **ABSTRACT**

Provided are a plasma light source capable of solving a problem occurring when an arc discharge lamp is used and an inspection apparatus capable of providing uniform and high-brightness plasma light. The plasma light source includes a pulse laser generator configured to generate a pulse laser beam, a continuous wave (CW) laser generator configured to generate an infrared ray (IR) CW laser beam, a first dichroic mirror configured to transmit or reflect the pulse laser beam and reflect or transmit the IR CW laser beam, a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and discharge plasma light generated by the plasma, and a second dichroic mirror configured to transmit the pulse laser beam and the IR CW laser beam and reflect the plasma light.

14 Claims, 25 Drawing Sheets



[illegible]

FIG. 1A

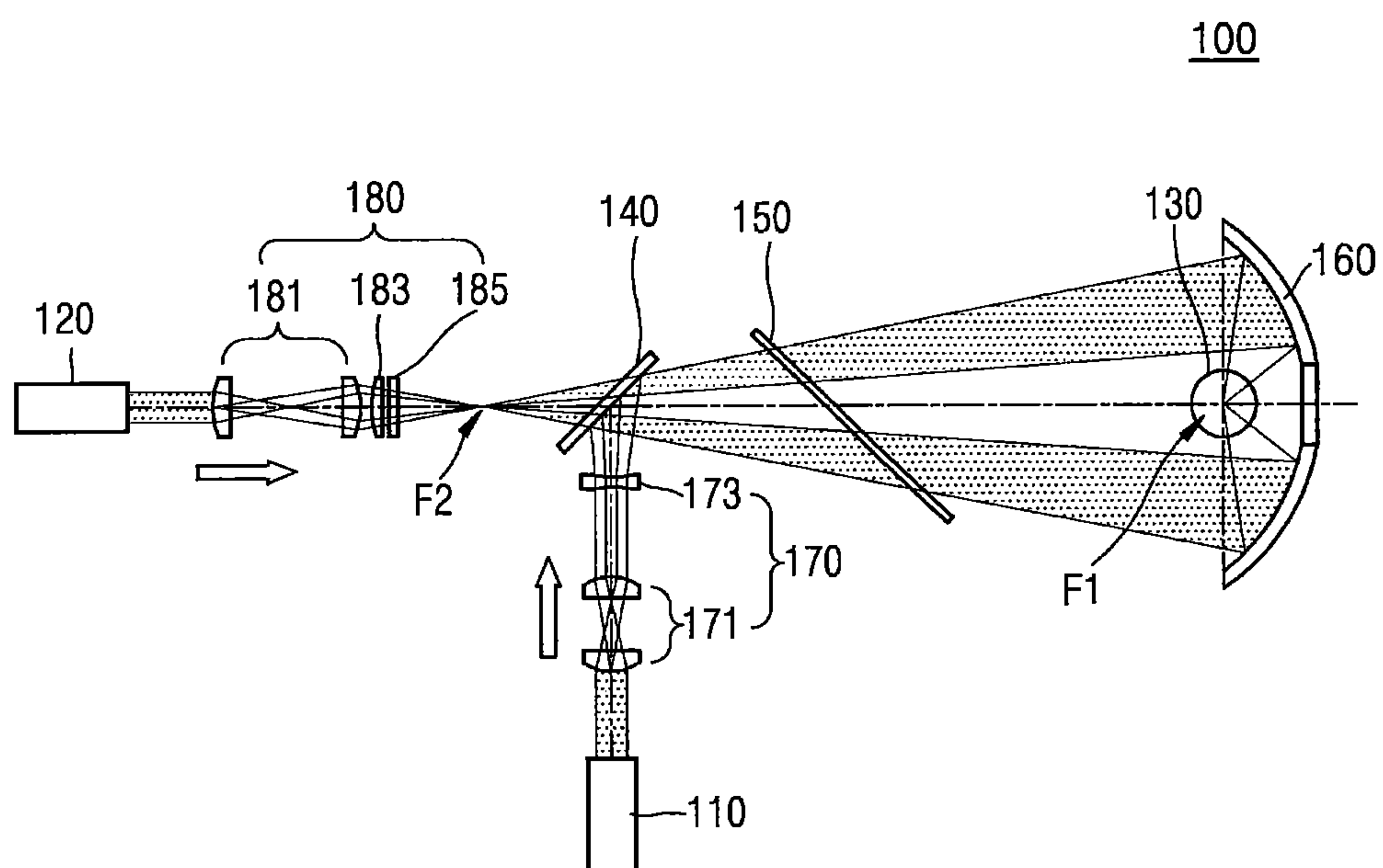


FIG. 1B

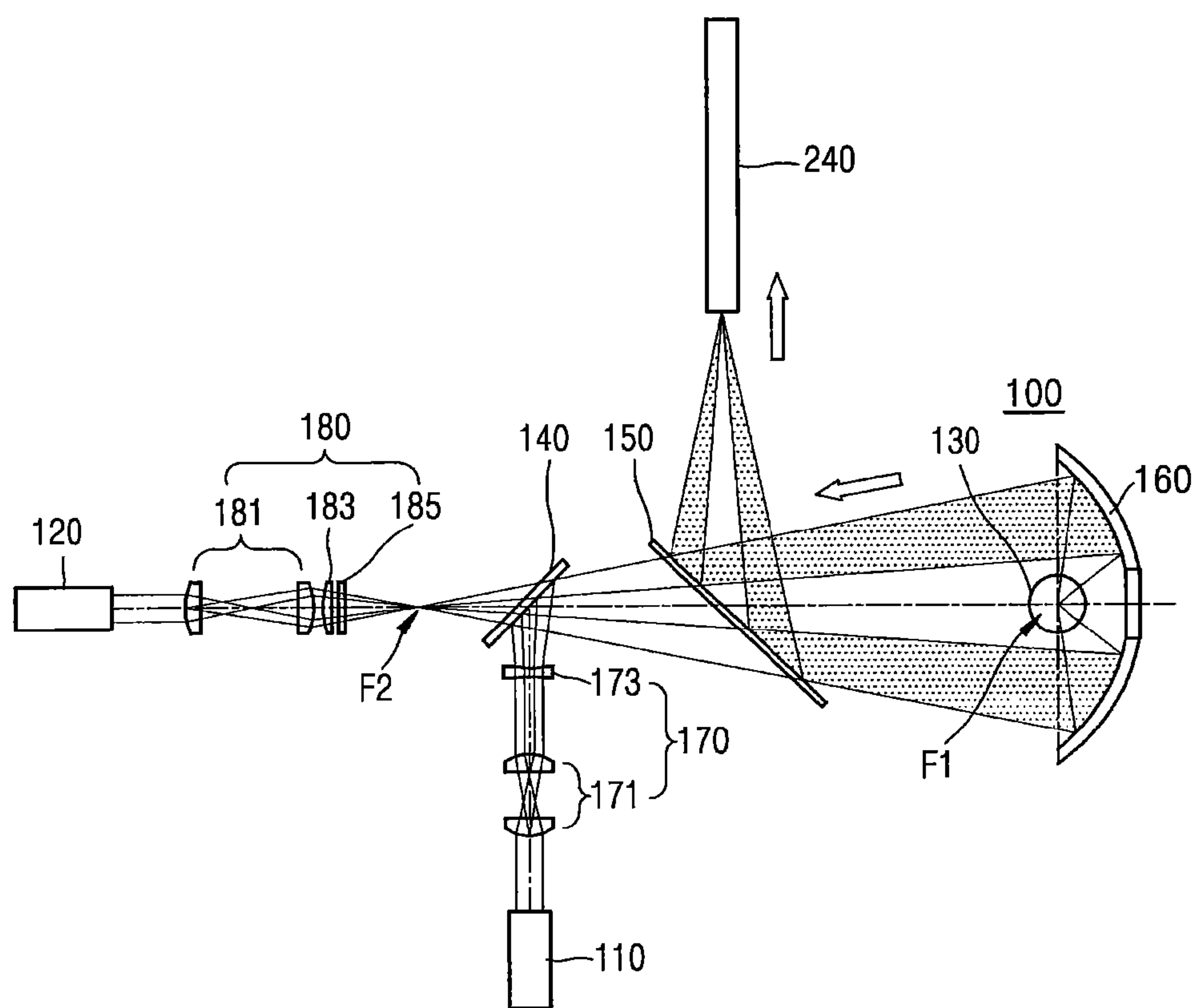


FIG. 2

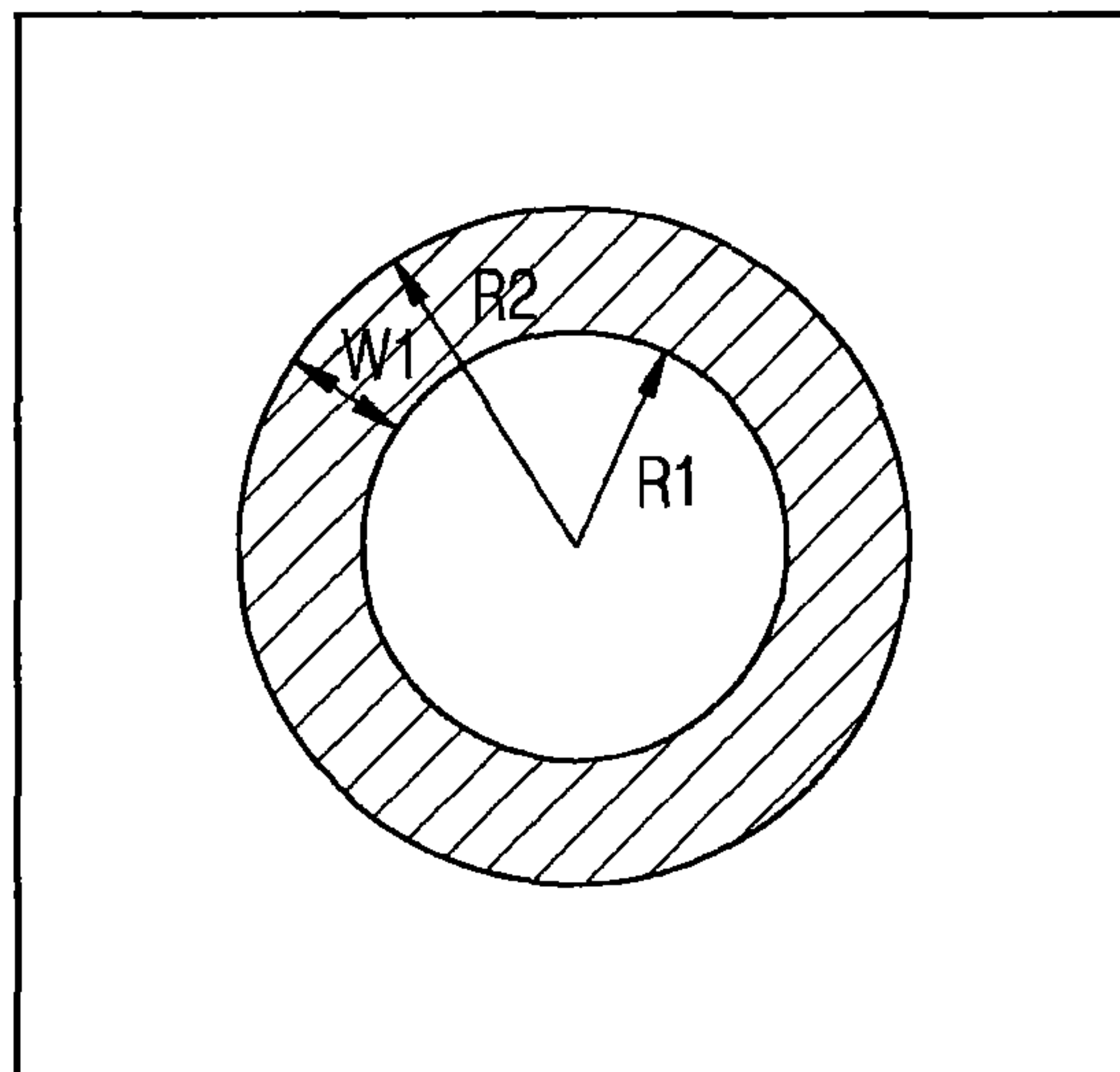


FIG. 3

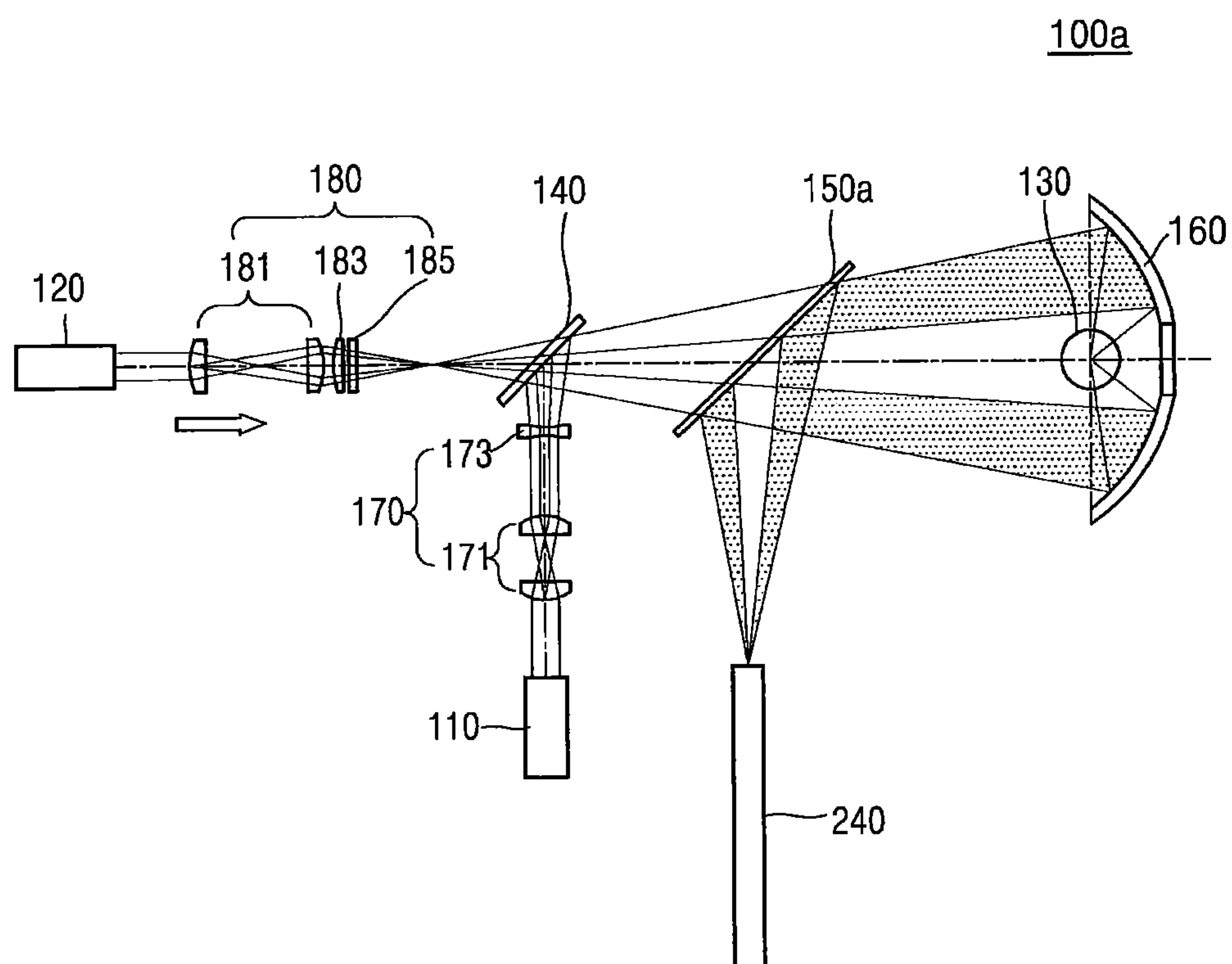


FIG. 4

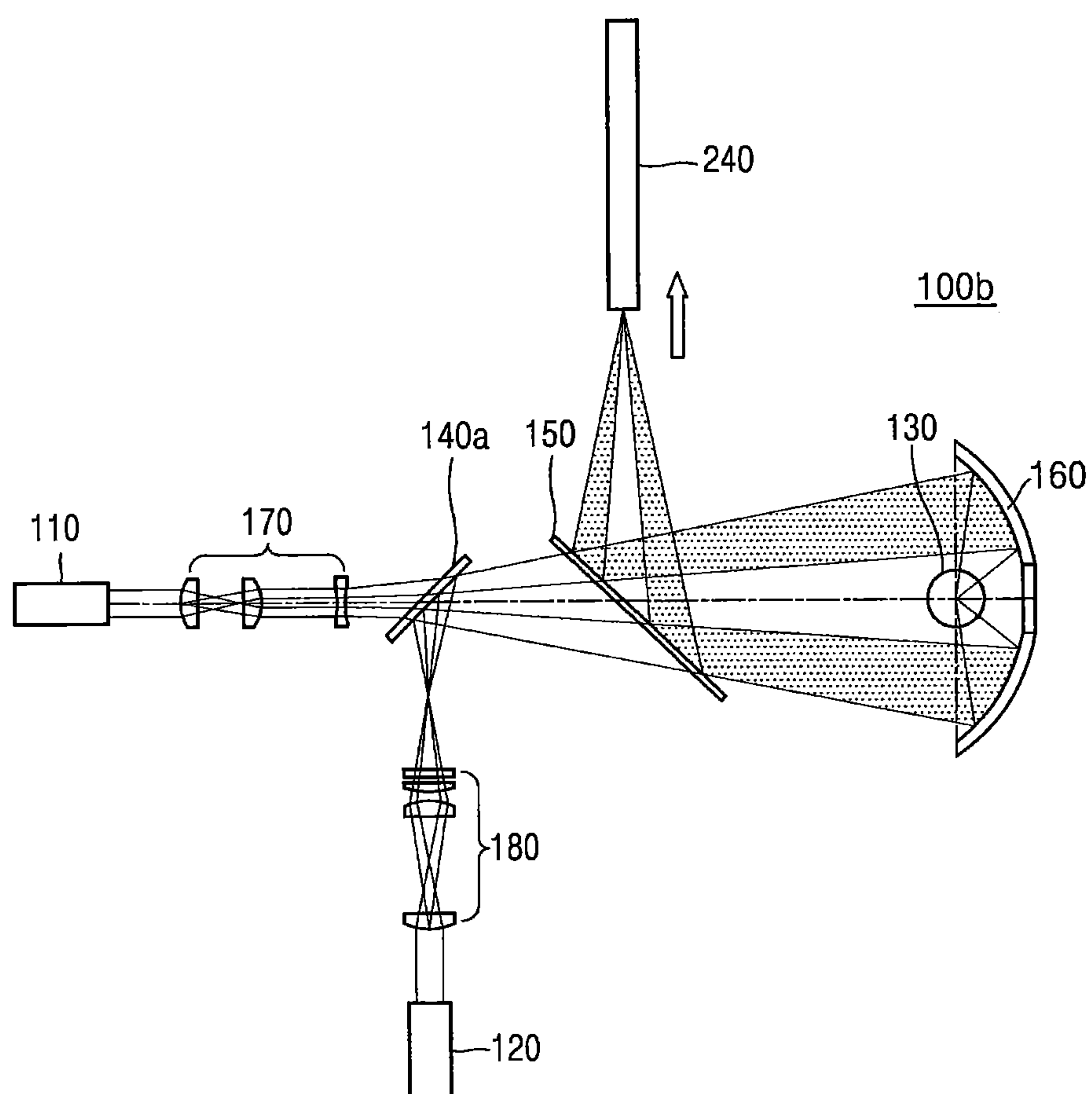


FIG. 5

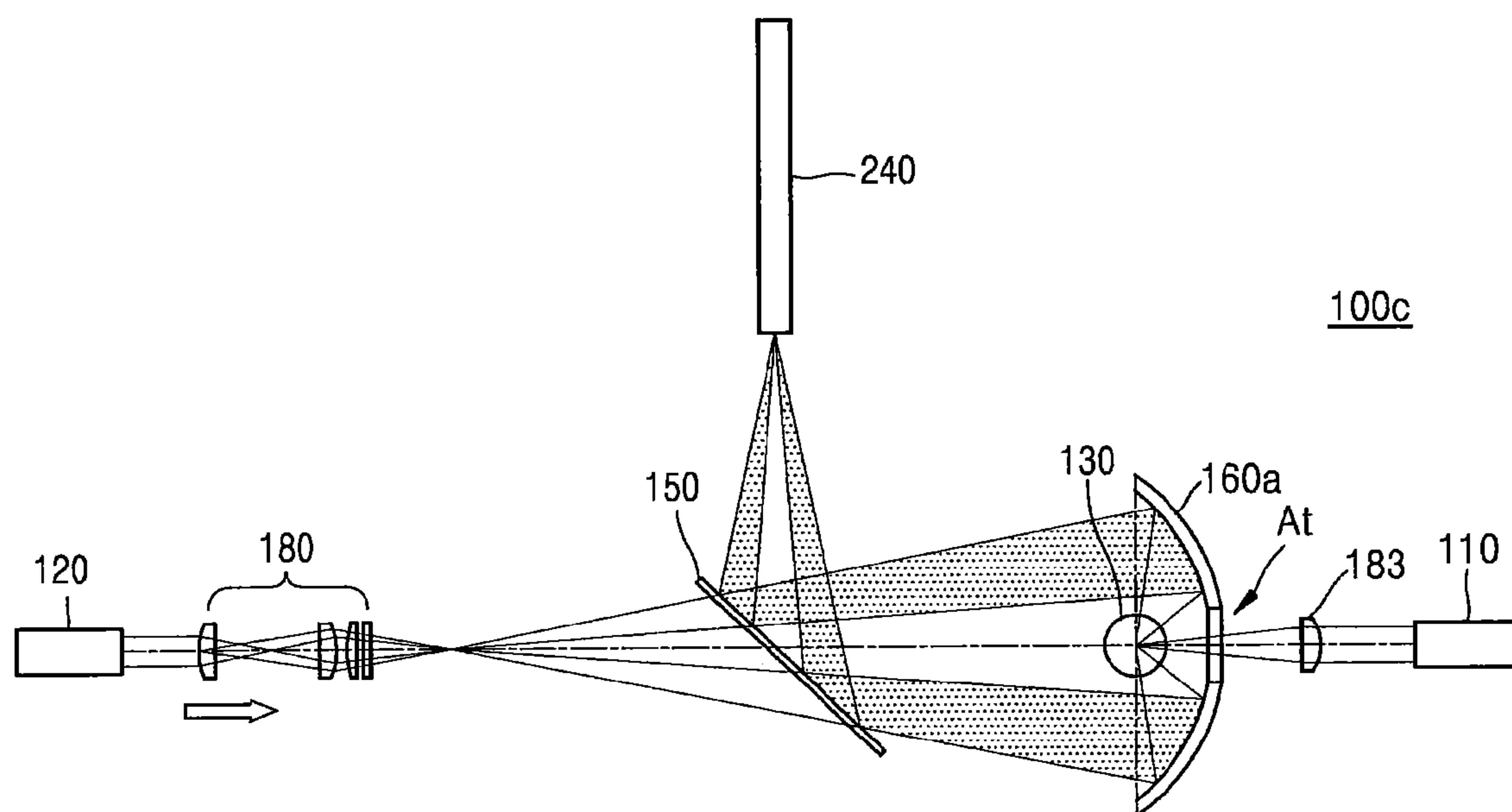


FIG. 6

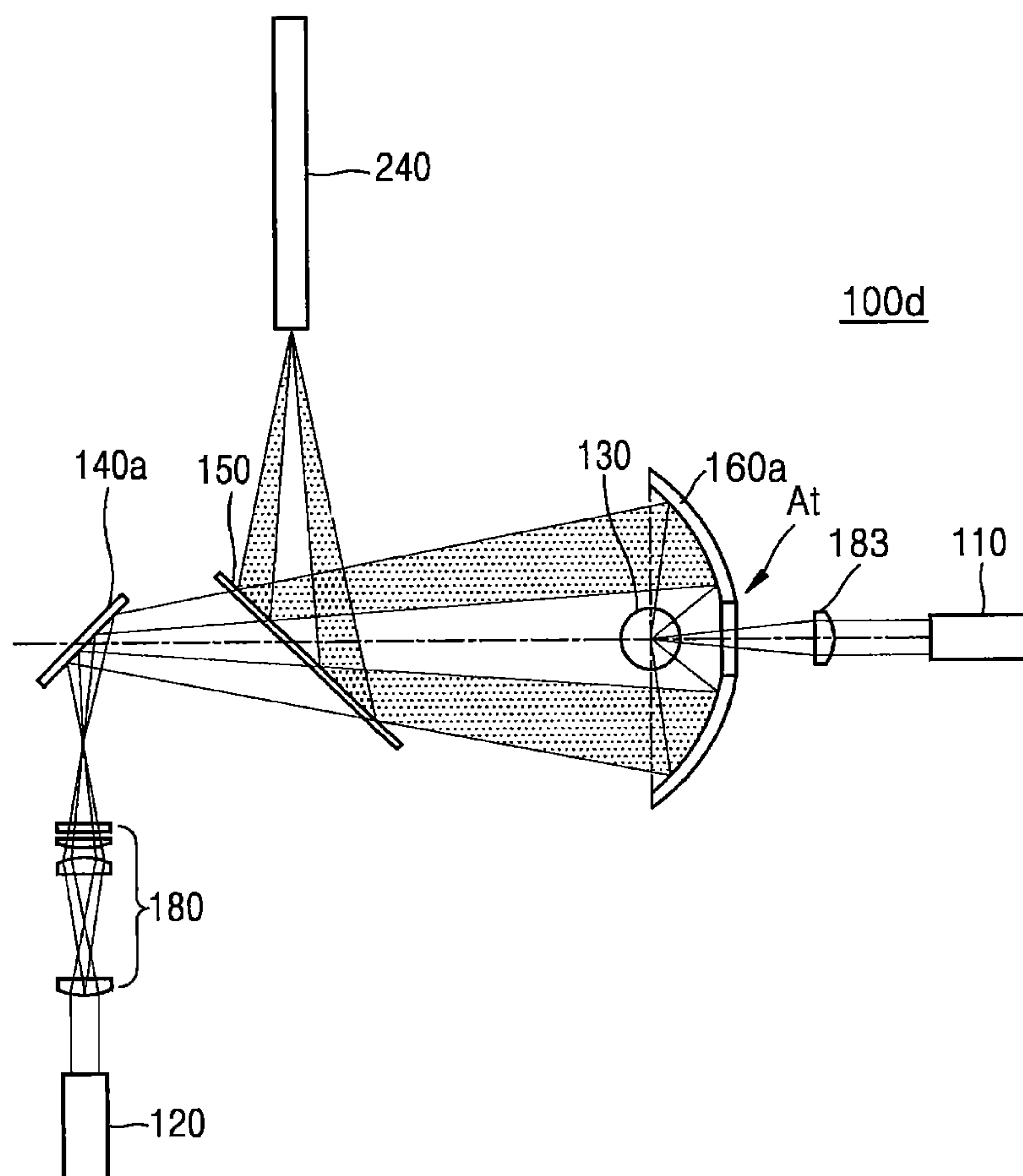


FIG. 7

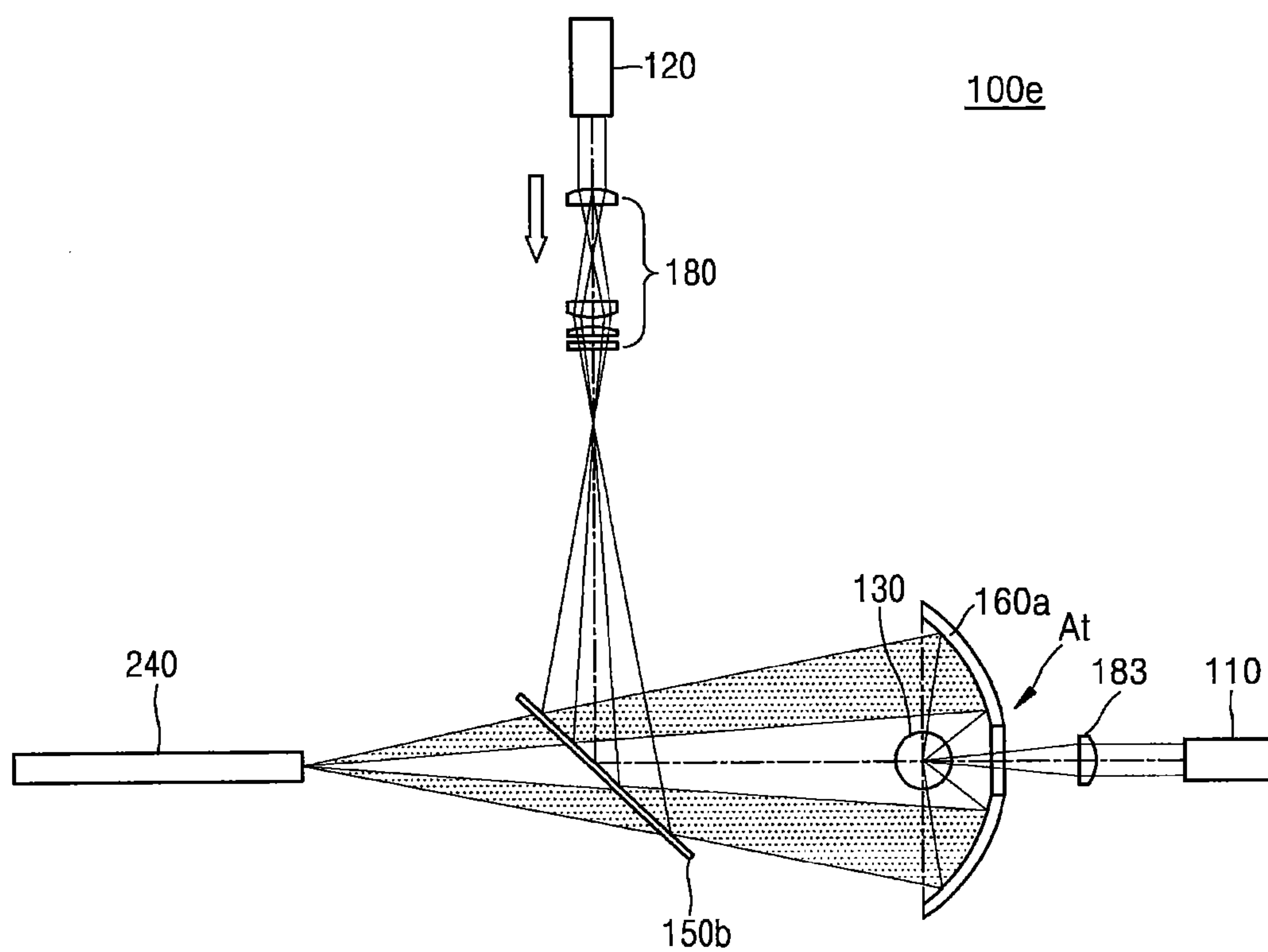


FIG. 8

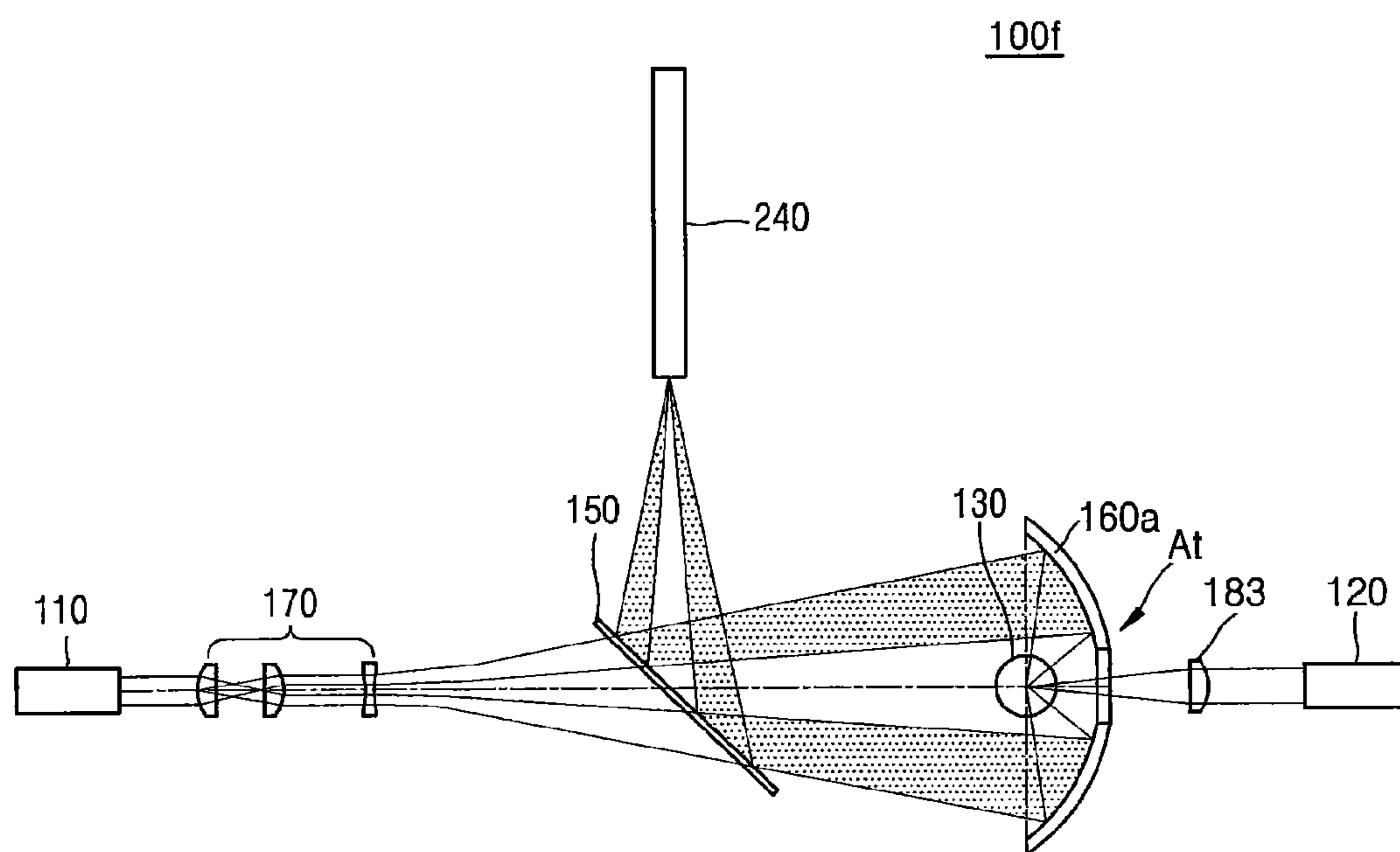


FIG. 9

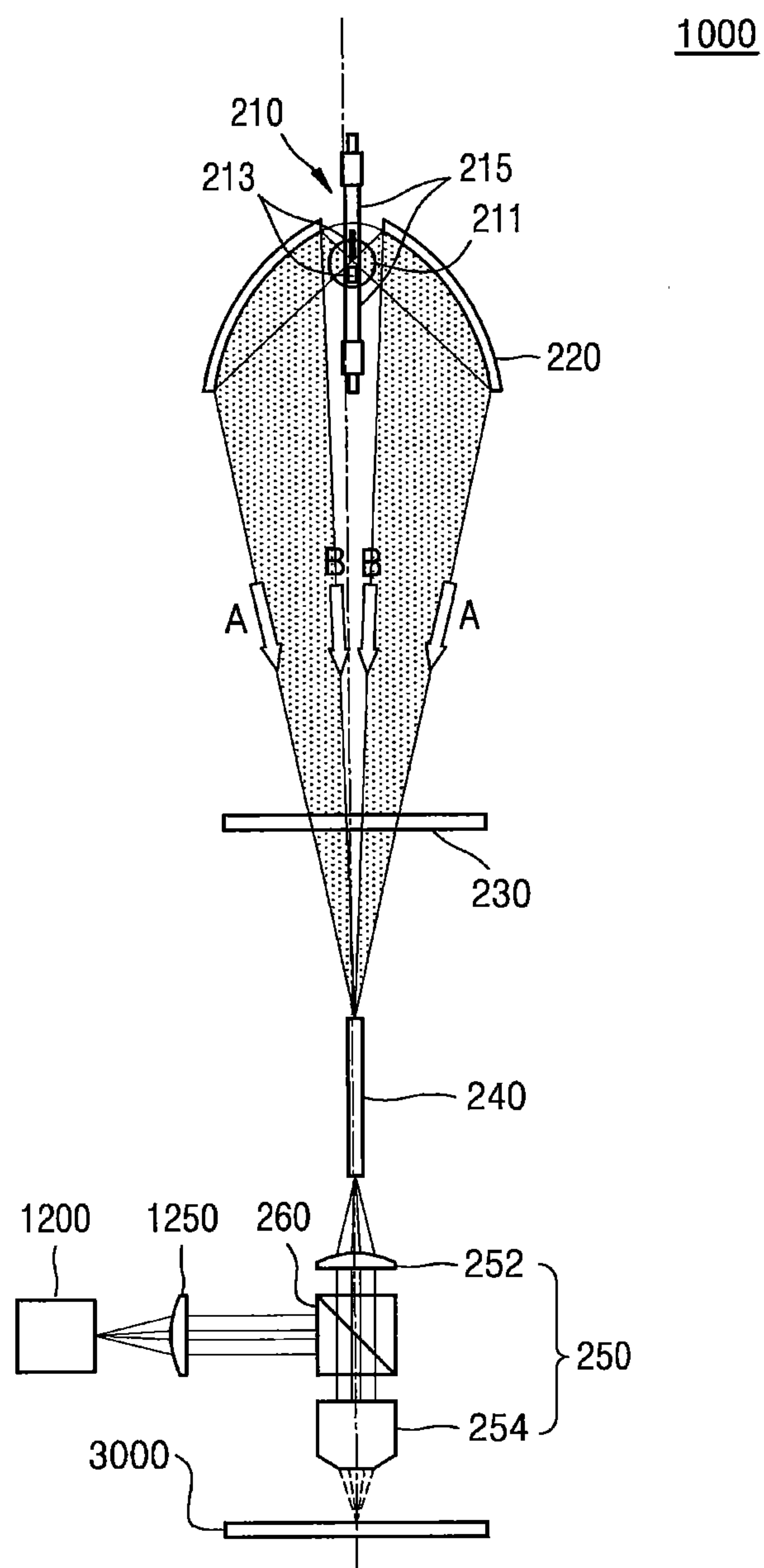


FIG. 10

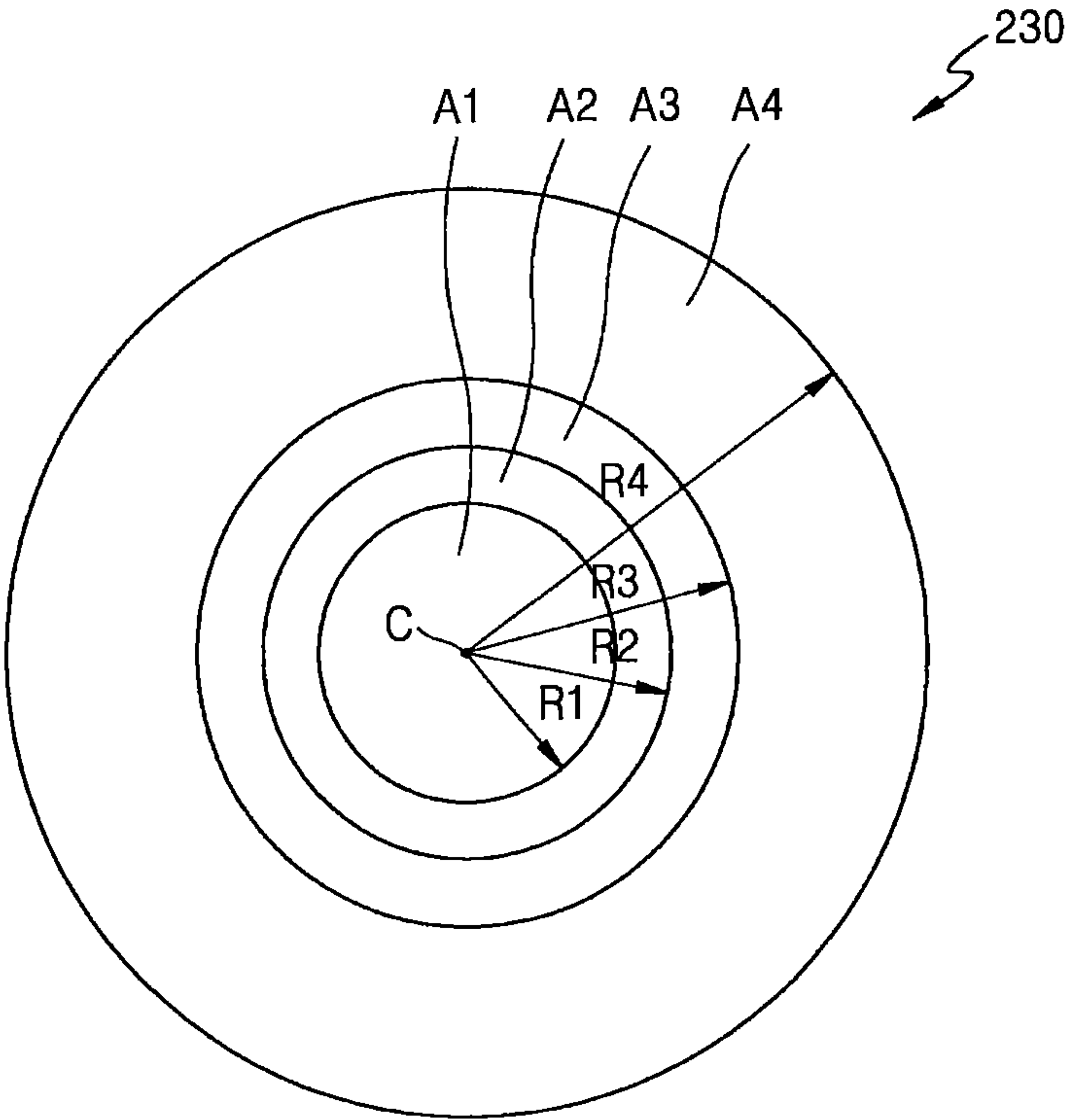


FIG. 11A

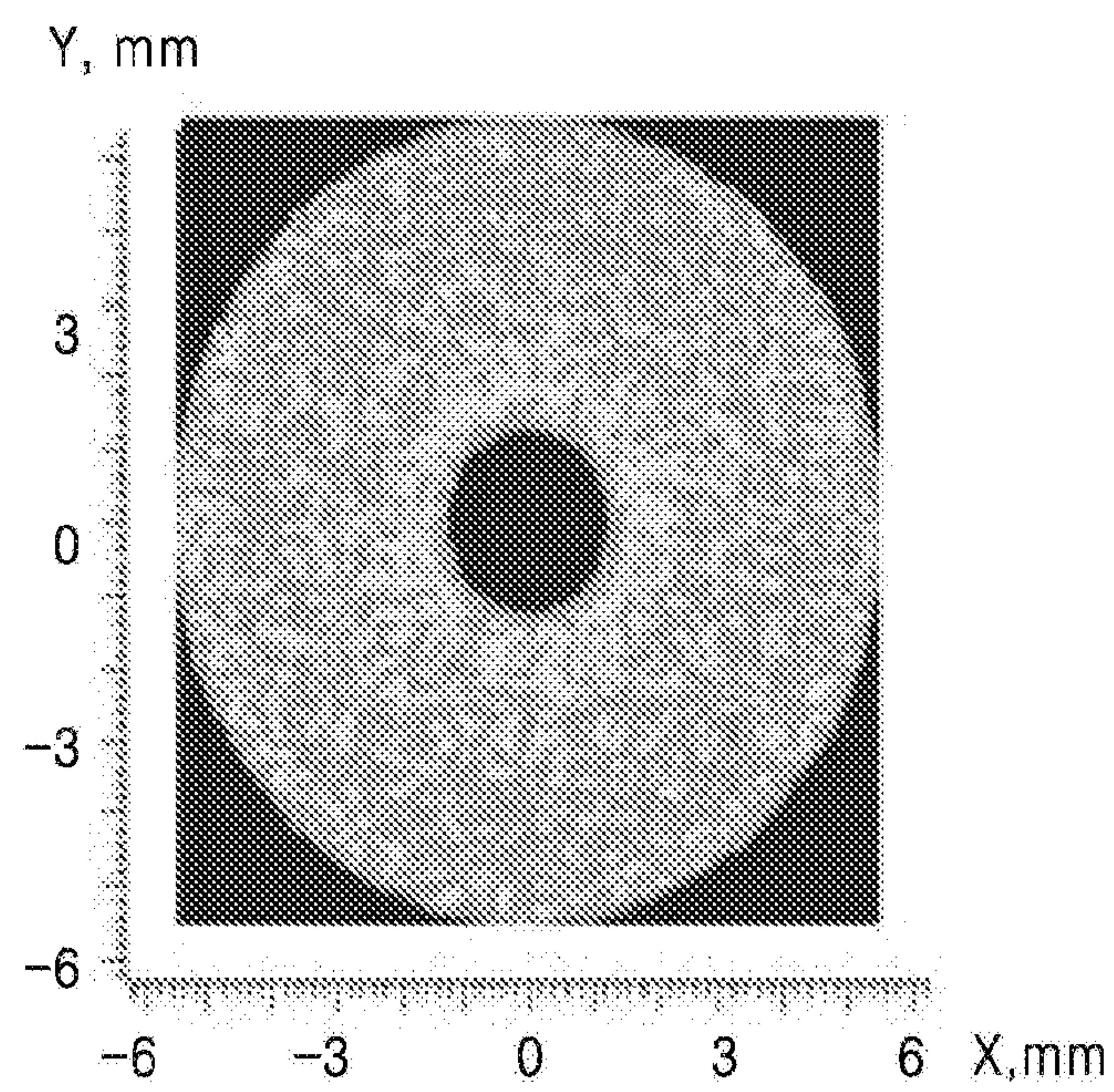
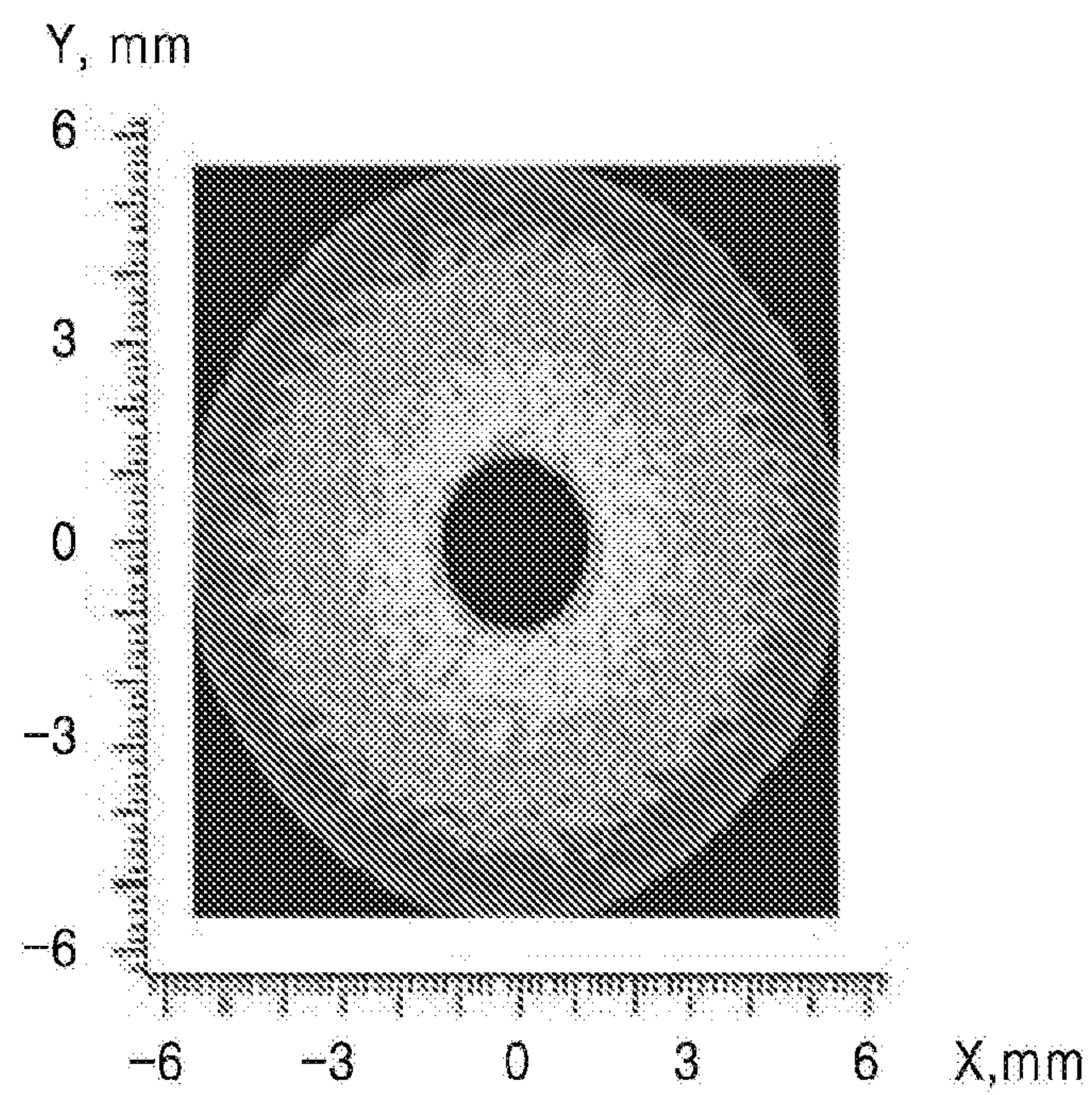


FIG. 11B

FIG. 12 A

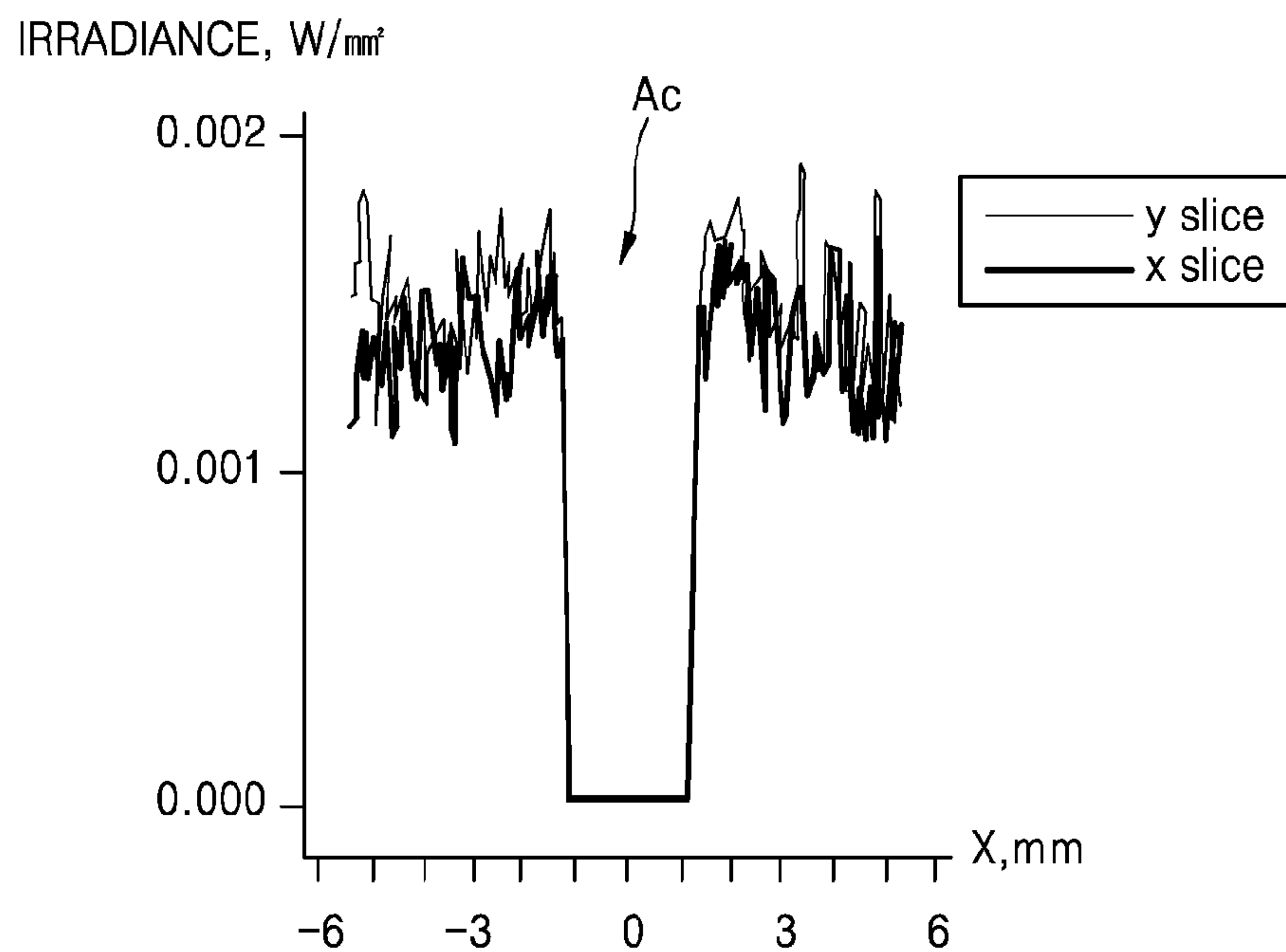
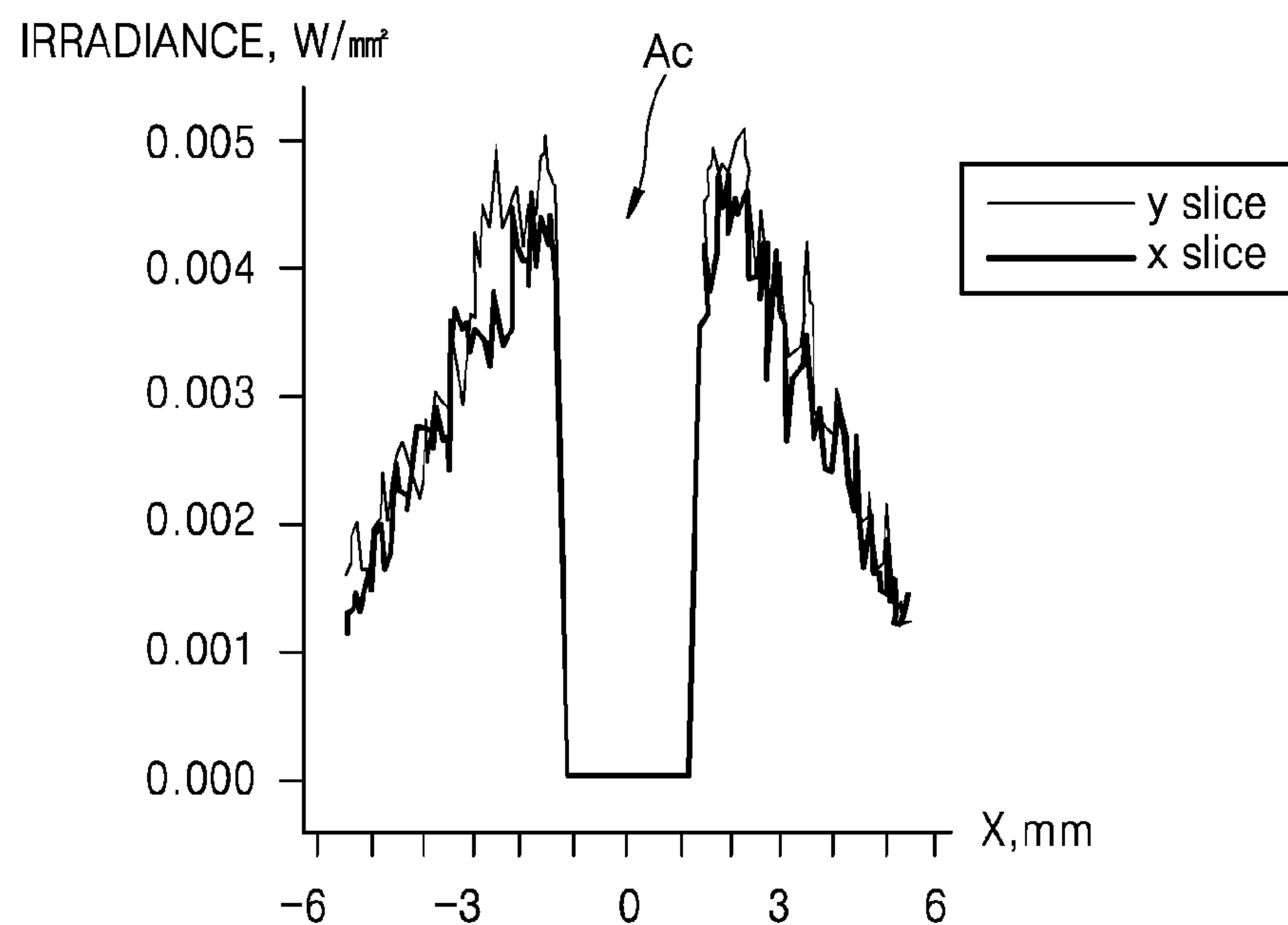


FIG 12B

FIG. 13

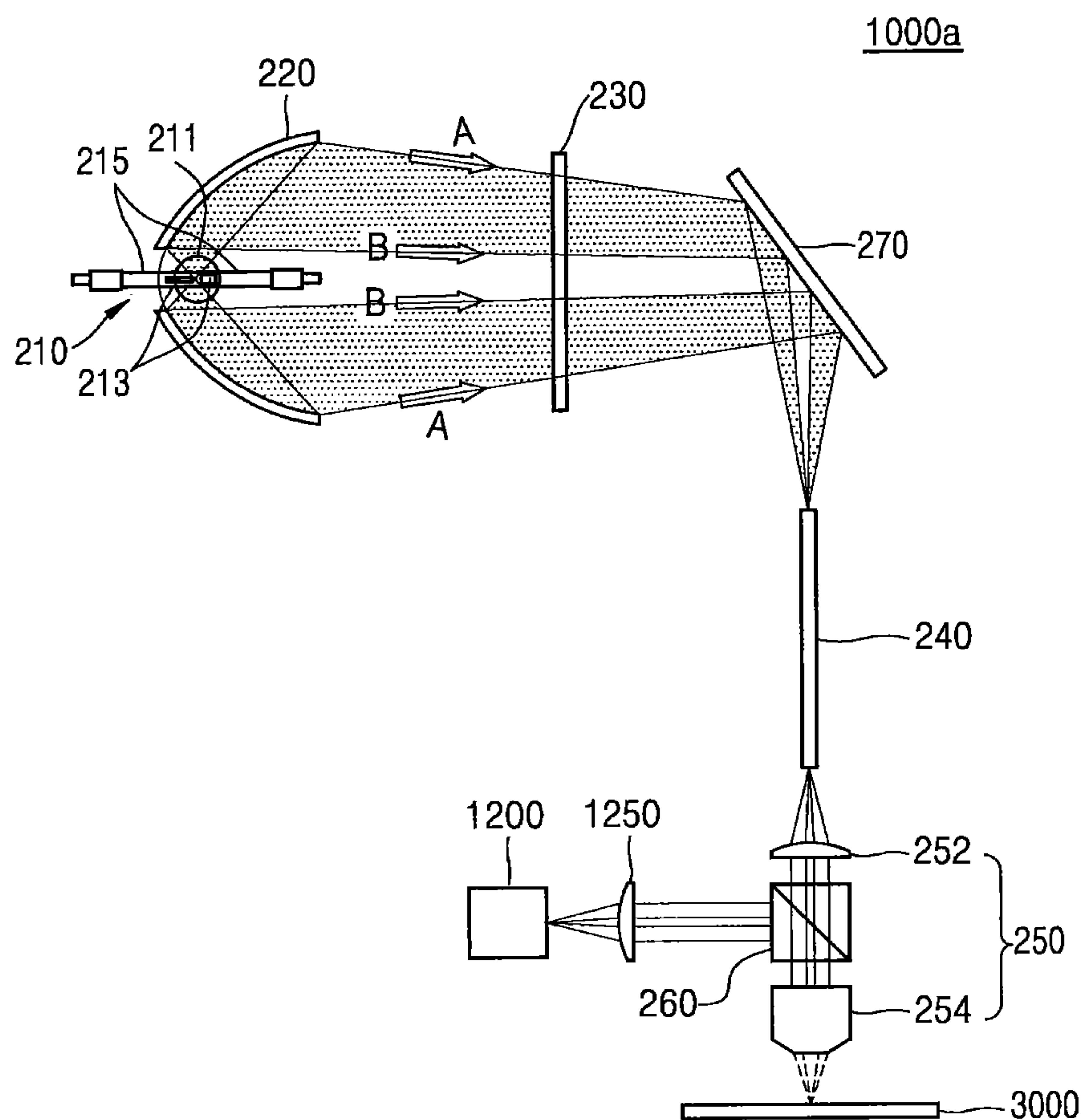


FIG. 14

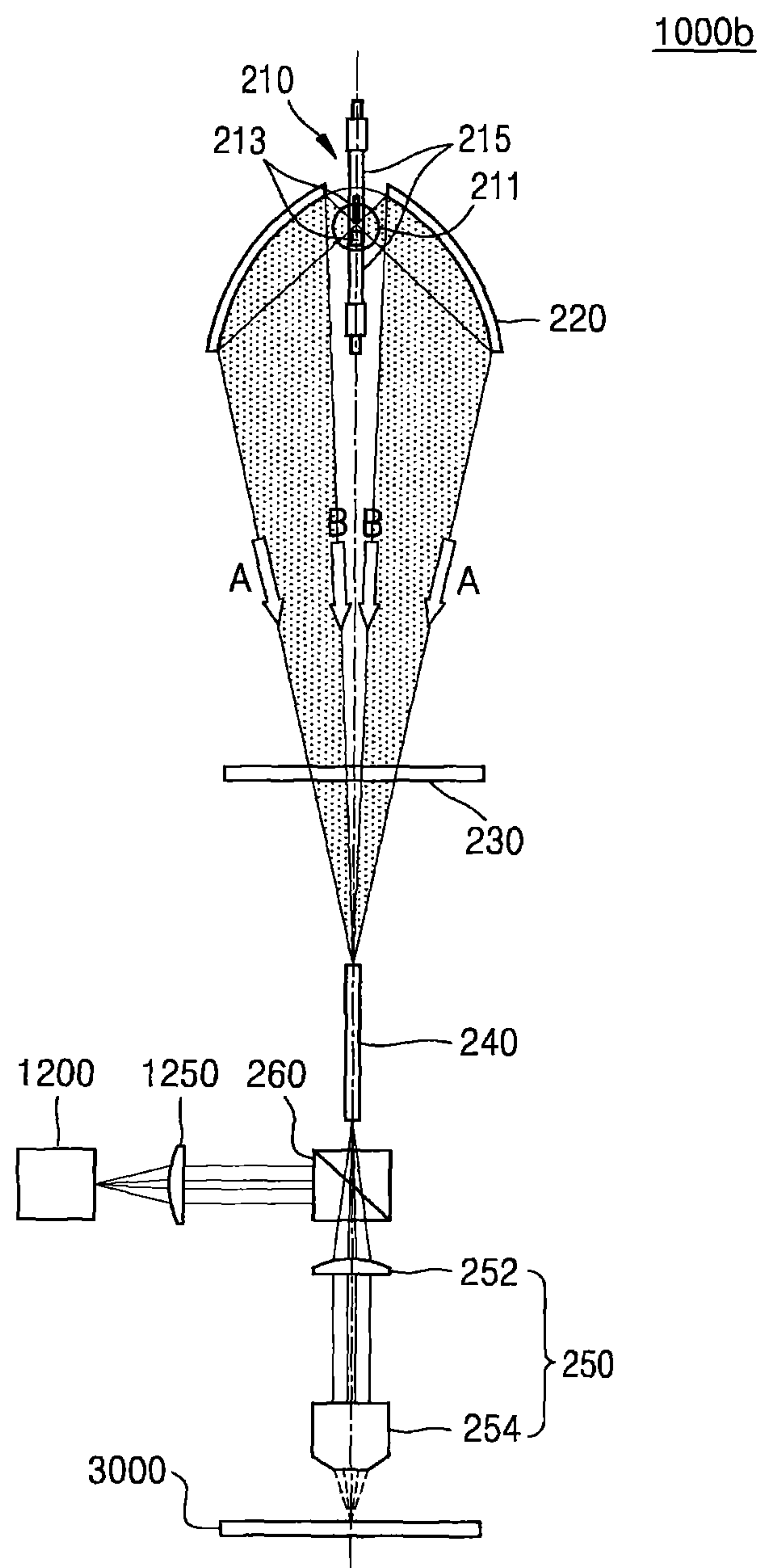


FIG. 15

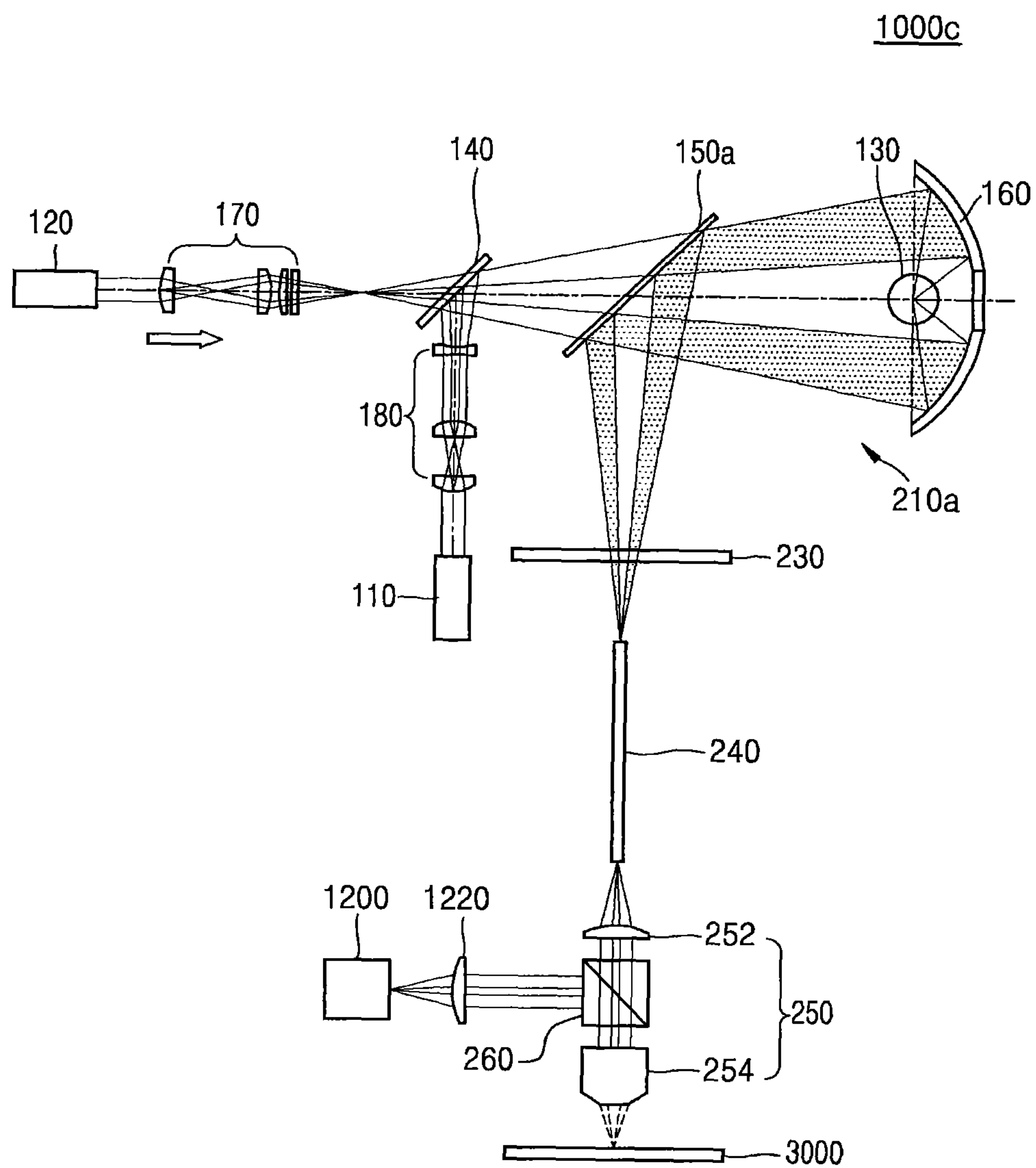


FIG. 16

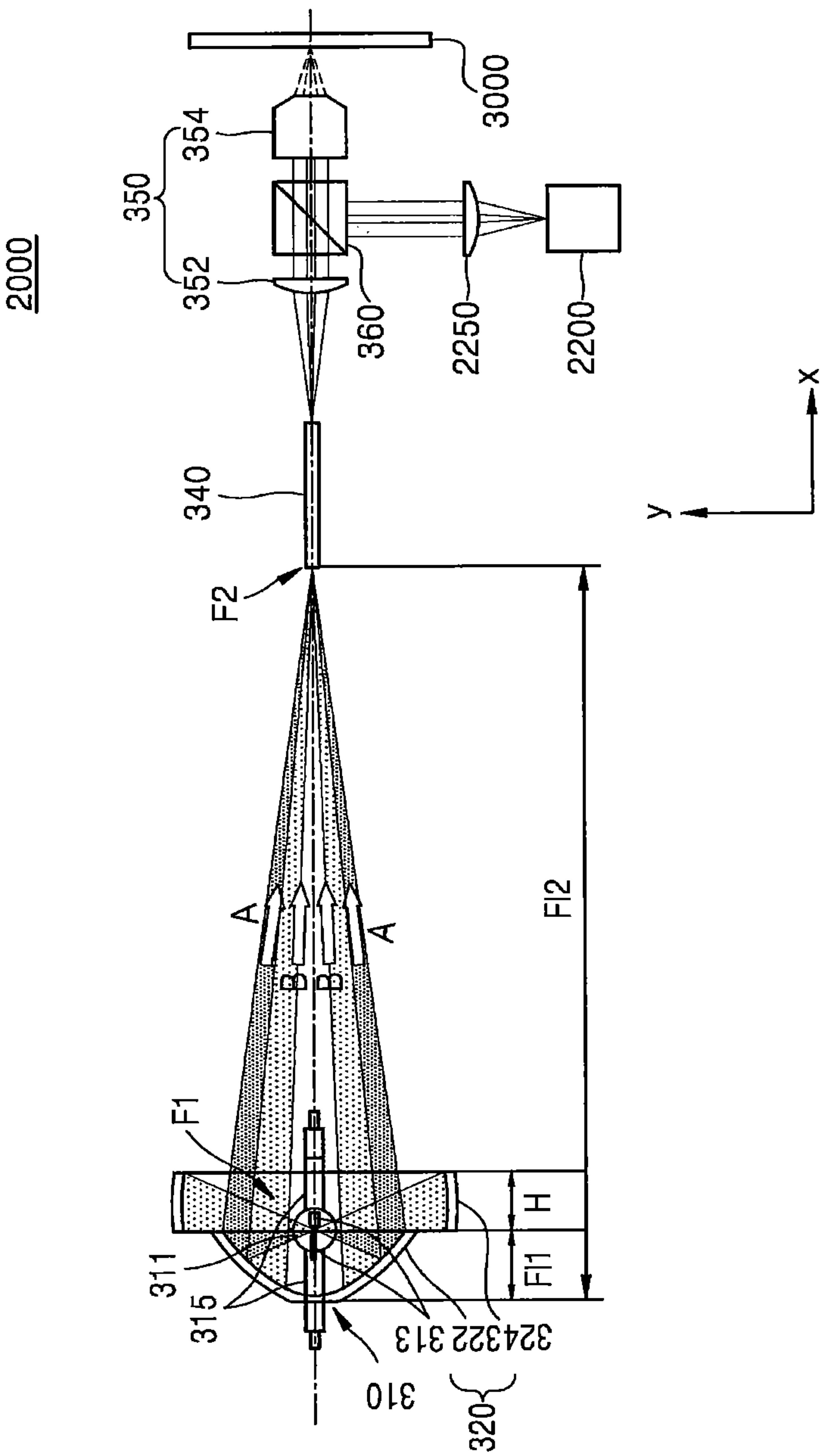


FIG. 17

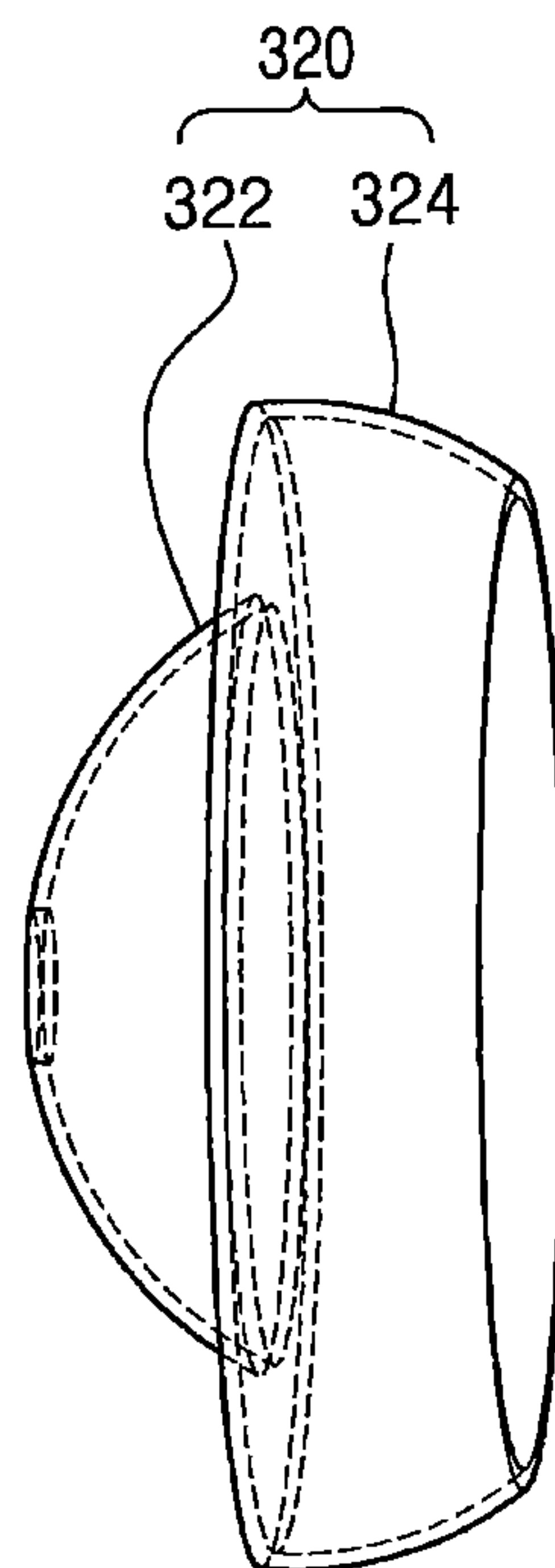


FIG. 18

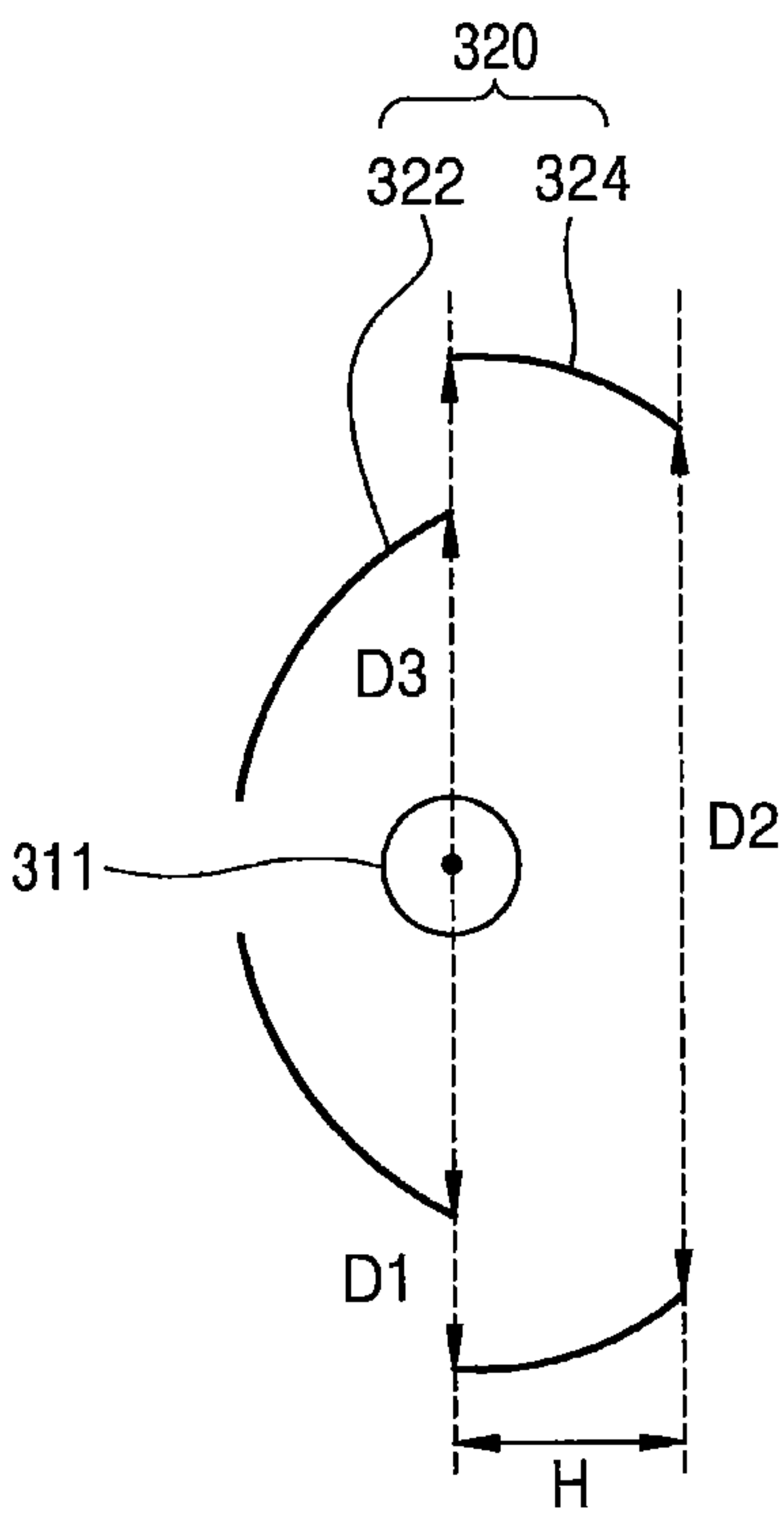


FIG. 19

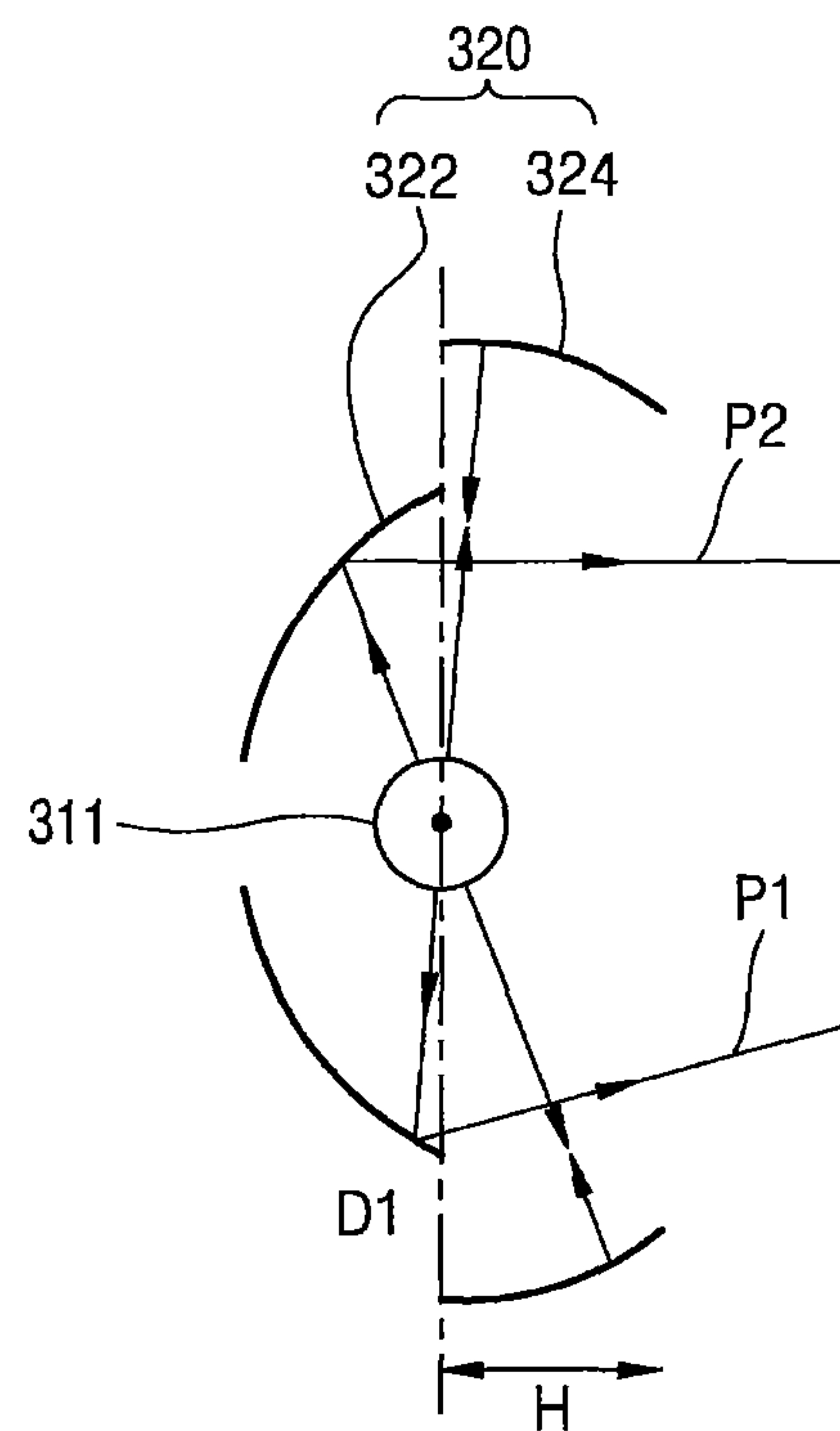


FIG. 20A

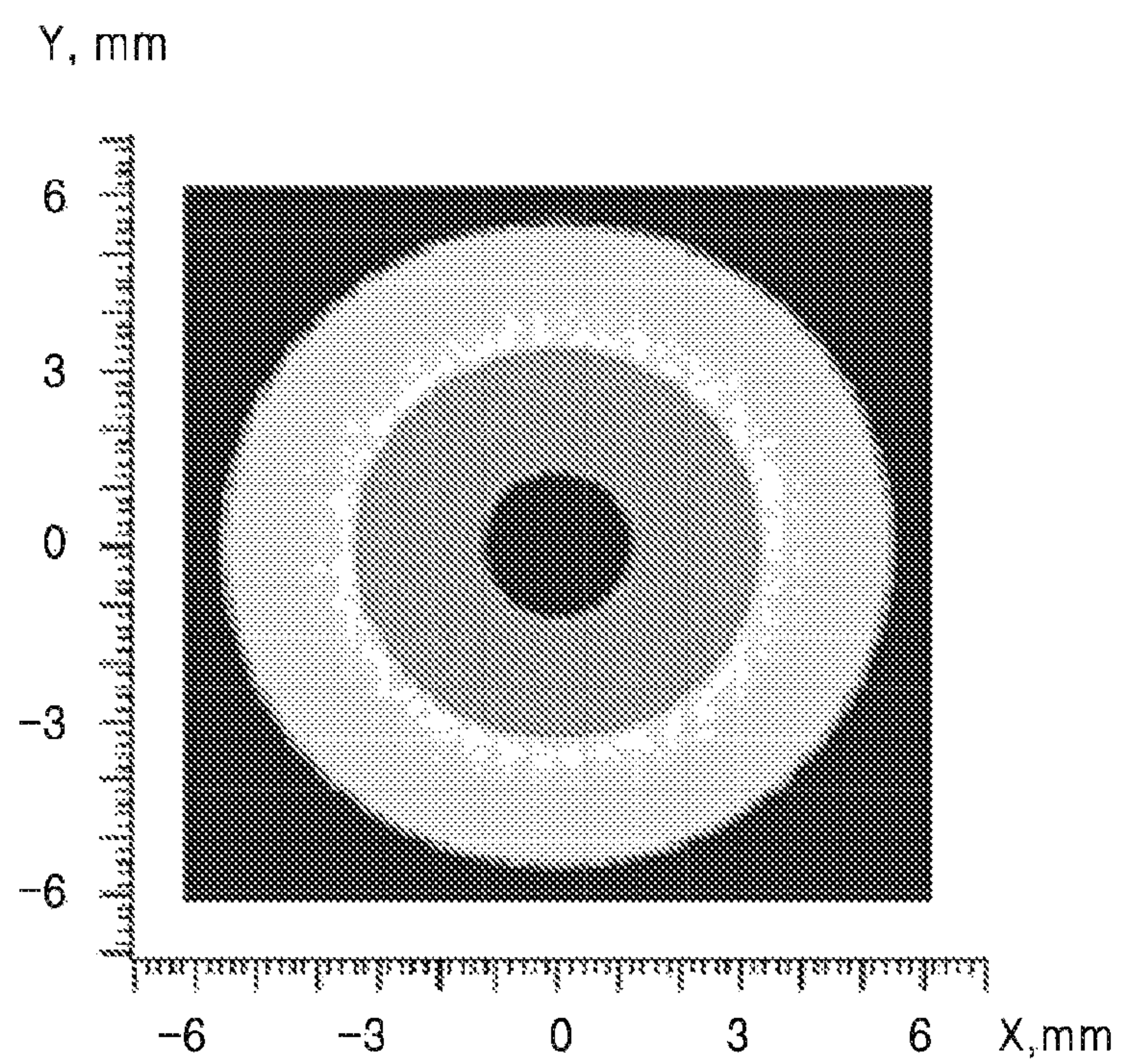
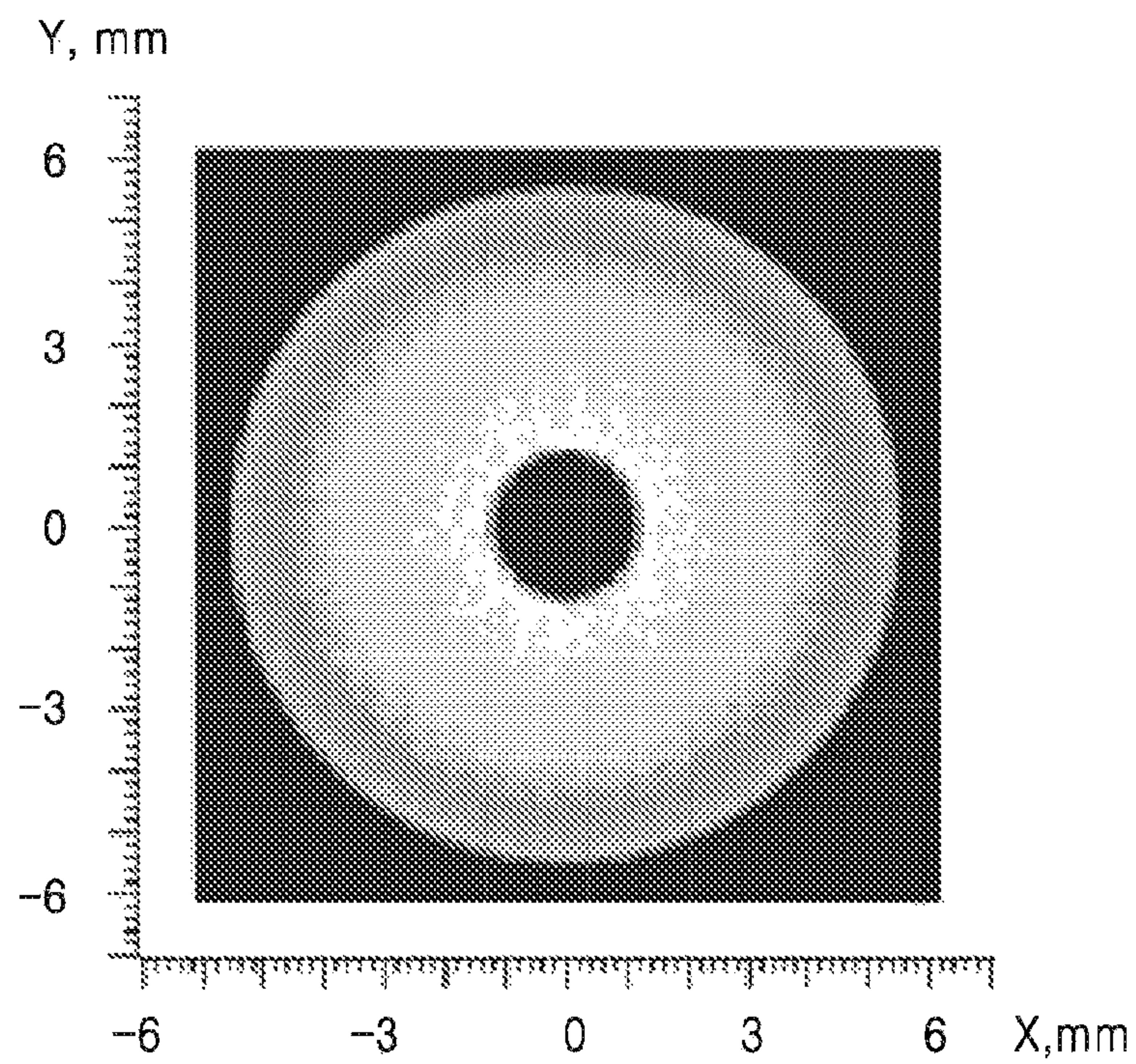


FIG. 20B

FIG. 21A

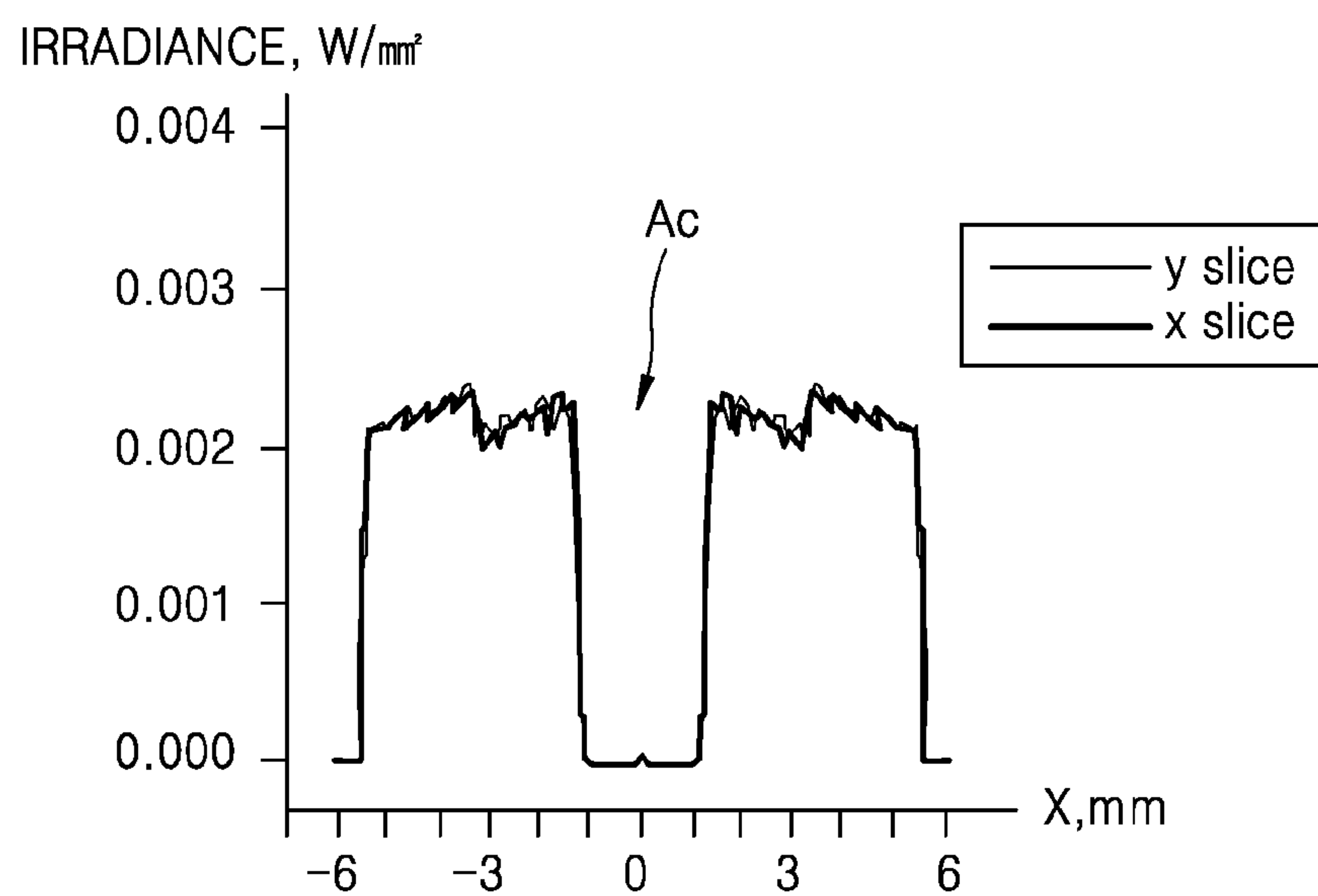
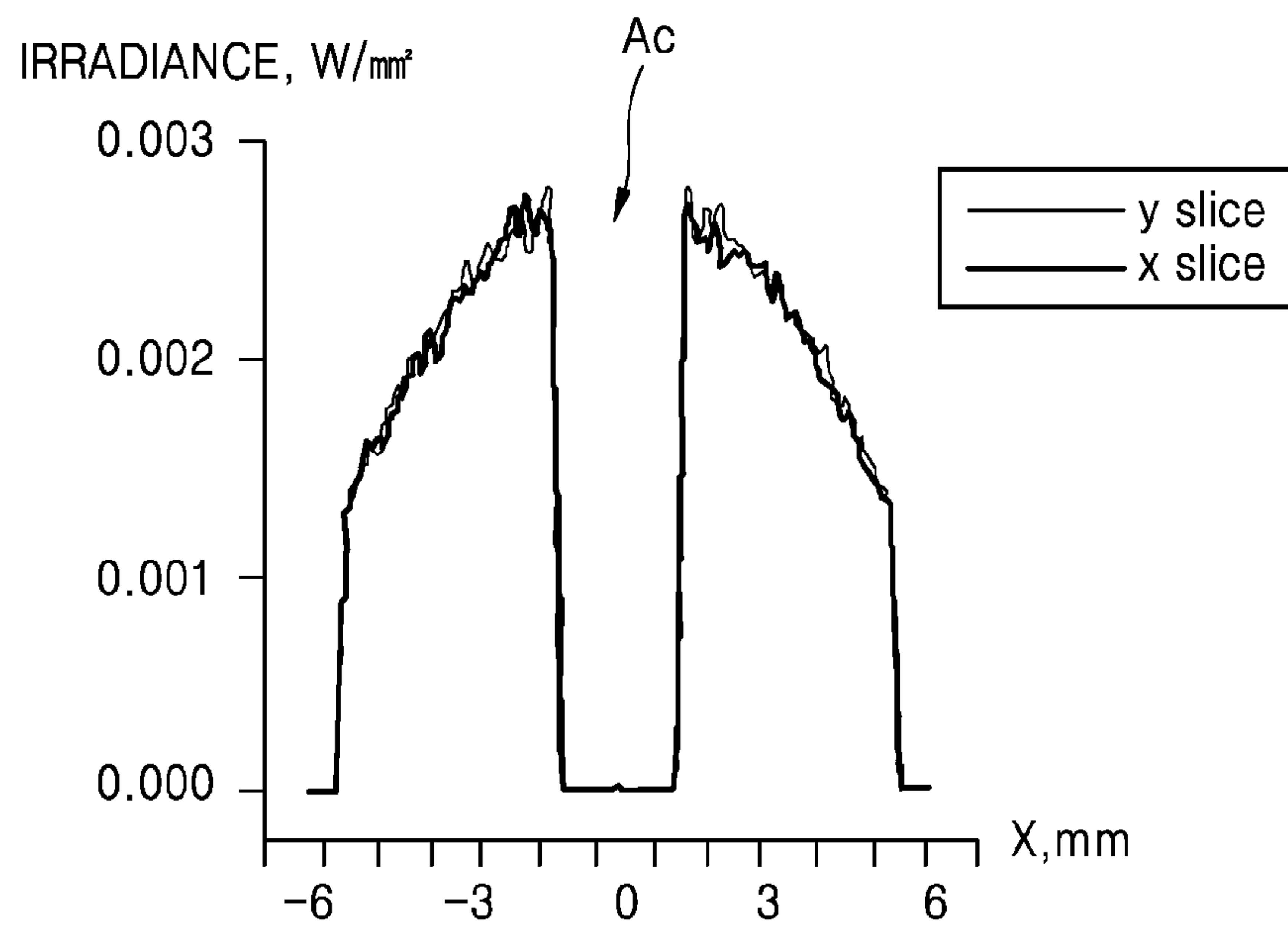


FIG. 21B

FIG. 22

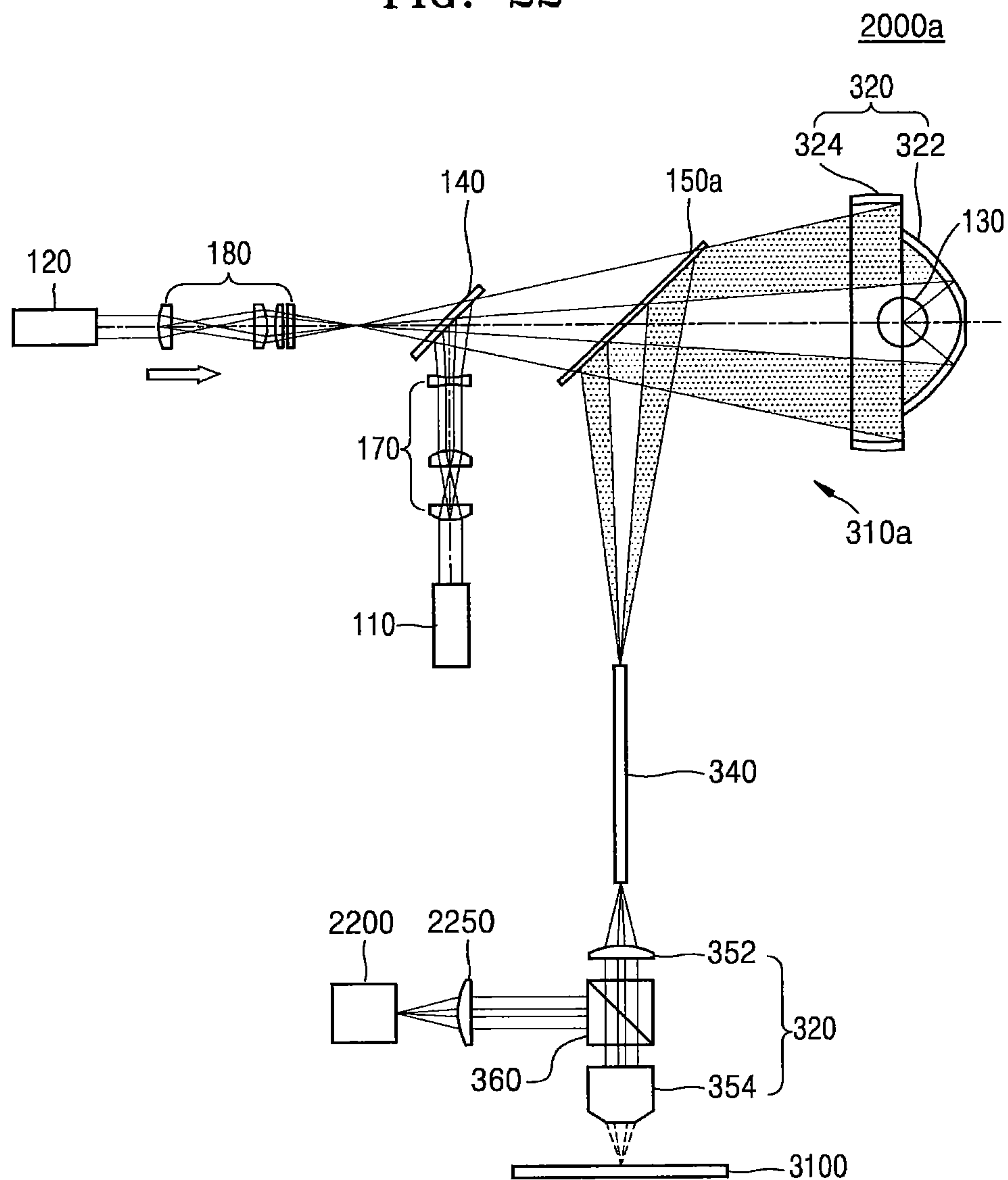


FIG. 23

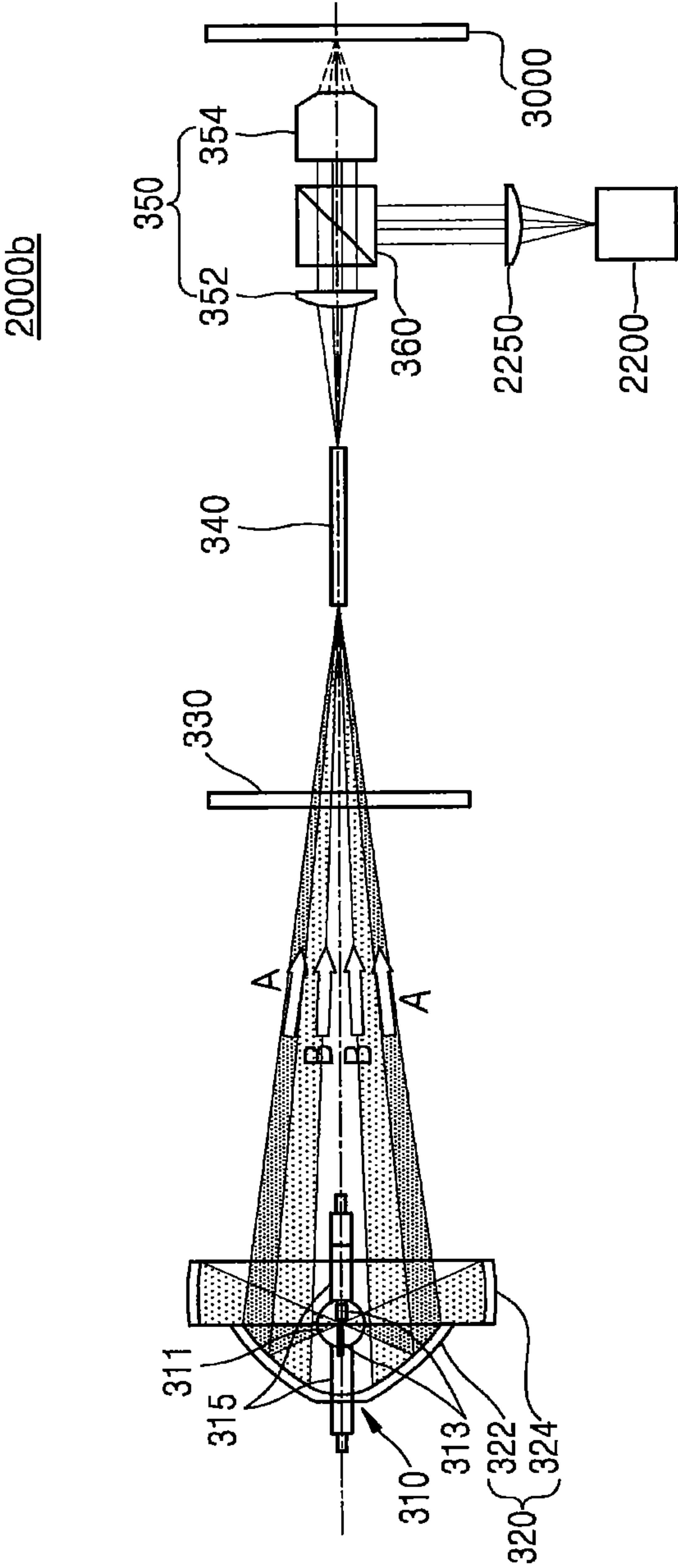
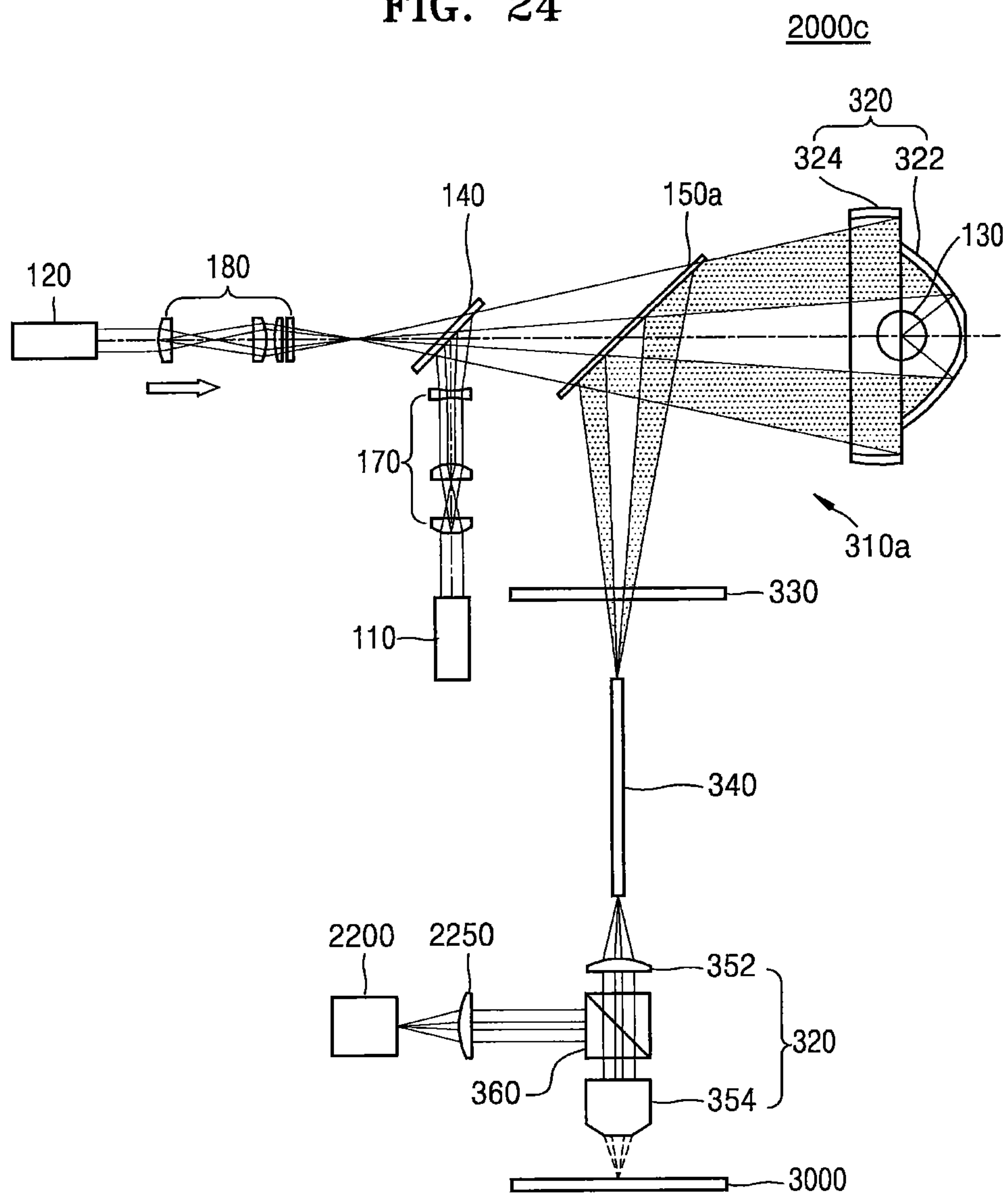


FIG. 24



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**PLASMA LIGHT SOURCE AND INSPECTION
APPARATUS INCLUDING THE SAME****CROSS-REFERENCE TO RELATED
APPLICATION**

This application claims priority to Korean Patent Application No. 10-2014-0178713, filed on Dec. 11, 2014, the disclosure of which is incorporated by reference herein in its entirety.

BACKGROUND

The inventive concept relates to a light source and an inspection apparatus, and more particularly, to a plasma light source for use in a semiconductor manufacturing process or an inspection process, and an inspection apparatus capable of providing high-brightness plasma light.

High-brightness light sources may be used in various applications. For example, the high-brightness light sources may be used to examine, test, or measure characteristics of semiconductor wafers or materials used in manufacturing semiconductor wafers. In addition, electromagnetic energy, which is produced by the high-brightness light source, may be used in a lithography system, a microscopy system, or a photoresist curing system, which is used in manufacturing wafers. On the other hand, parameters of light, such as a wavelength, a power level, and brightness, may be different depending on the fields of applications. Specifically, for example, a wafer inspection system supplies light by using xenon or mercury arc lamps. The arc lamps may include a positive electrode and a negative electrode for exciting xenon or mercury gas within a lamp. When the arc lamp generates light, the positive electrode and the negative electrode may be worn out, or contaminant particles may be generated. Furthermore, in some fields, in particular, in the fields of ultraviolet spectrum, satisfactory brightness may not be provided.

SUMMARY

The inventive concept provides a plasma light source capable of solving a problem occurring when an arc discharge lamp is used, and an inspection apparatus capable of providing uniform and high-brightness plasma light.

According to an aspect of the inventive concept, there is provided a plasma light source including a pulse laser generator configured to generate a pulse laser beam, a continuous wave (CW) laser generator configured to generate an infrared ray (IR) CW laser beam, a first dichroic mirror configured to transmit or reflect the pulse laser beam and reflect or transmit the IR CW laser beam, a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and to discharge plasma light generated by the plasma, and a second dichroic mirror configured to transmit the pulse laser beam and the IR CW laser beam and reflect the plasma light.

In some embodiments, the chamber has no electrodes therein.

In some embodiments, the chamber is surrounded by an elliptical mirror and is disposed at a focus of the elliptical mirror, and the pulse laser beam and the IR CW laser beam are concentrated on the chamber by the elliptical mirror.

In some embodiments, the first dichroic mirror and the second dichroic mirror are disposed on a same axis to selectively reflect or transmit light according to a wave-

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length, so that input light beams incident on the chamber are synthesized and an output light beam from the chamber is separated from the input light beams.

In some embodiments, the pulse laser beam is input to the chamber by reflection of the first dichroic mirror and transmission of the second dichroic mirror, and the IR CW laser beam passes through the first dichroic mirror and the second dichroic mirror and is input to the chamber. In some embodiments, a concave lens is disposed between the pulse laser generator and the first dichroic mirror, and a cylindrical lens is disposed between the CW laser generator and the first dichroic mirror.

In some embodiments, the pulse laser beam and the IR CW laser beam are ring-shaped beams and are input to the first dichroic mirror. In some embodiments, the ring-shaped beams are formed using a pair of axicon lenses or a spatial light modulator (SLM).

According to another aspect of the inventive concept, there is provided a plasma light source including a first dichroic mirror configured to transmit or reflect a pulse laser beam and reflect or transmit an infrared ray (IR) continuous wave (CW) laser beam, a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and discharge plasma light generated by the plasma, a second dichroic mirror configured to transmit or reflect the pulse laser beam and the IR CW laser beam and to reflect the plasma light, and a reflection structure including a combination of an elliptical mirror and a spherical mirror and configured to homogenize the plasma light in terms of angle by reflection of the elliptical mirror and the spherical mirror so that the plasma light is directed in one direction.

In some embodiments, the pulse laser beam and the IR CW laser beam are ring-shaped beams and are input to the first dichroic mirror.

In some embodiments, the pulse laser beam is input to the chamber by reflection of the first dichroic mirror and transmission of the second dichroic mirror, the IR CW laser beam passes through the first dichroic mirror and the second dichroic mirror and is input to the chamber, and the plasma light is output by reflection of the second dichroic mirror.

In some embodiments, the elliptical mirror has a structure that is opened in one direction, the spherical mirror is opened in a first direction and a second direction, the first direction being directed toward the elliptical mirror and the second direction being directed toward the one direction, and the reflection structure is configured such that an opened portion of the spherical mirror in the first direction is coupled to an opened portion of the elliptical mirror. In some embodiments, the spherical mirror reflects the plasma light, which is not reflected by the elliptical mirror, toward the elliptical mirror. In some embodiments, a diameter of the opened portion of the spherical mirror in the first direction is greater than a diameter of the opened portion of the spherical mirror in the second direction, the diameter of the opened portion of the spherical mirror in the first direction is greater than a diameter of the opened portion of the elliptical mirror, and the opened portion of the spherical mirror in the second direction has a sufficient diameter to transmit the plasma light reflected by the elliptical mirror without being blocked. In some embodiments, the spherical mirror is configured to homogenize the intensity of the plasma light in a central area and the intensity of the plasma light in an outer peripheral area on a cross section perpendicular to a traveling direction of the plasma light. In some embodiments, the central area is an area where the plasma light is reflected by only the elliptical mirror, and the outer

peripheral area is an area where the plasma light is reflected by the elliptical mirror and the spherical mirror. In some embodiments, the elliptical mirror and the spherical mirror have a same focus, and the chamber is disposed at the same focus of the elliptical mirror and the spherical mirror.

According to another aspect of the inventive concept, there is provided an inspection apparatus including: a plasma light source including a first dichroic mirror configured to transmit or reflect a pulse laser beam and to reflect or transmit an infrared ray (IR) continuous wave (CW) laser beam, a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and discharge plasma light generated by the plasma, and a second dichroic mirror configured to transmit or reflect the pulse laser beam and the IR CW laser beam and reflect the plasma light, a homogenizer configured to receive the plasma light and spatially homogenize the plasma light, a uniformizing device configured to make the plasma light uniform in terms of angle and input the uniform plasma light to the homogenizer, a first optical system configured to transfer light output from the homogenizer to an inspection object, and an optical detector configured to detect light reflected from the inspection object.

In some embodiments, the chamber is surrounded by an elliptical mirror and is disposed at a focus of the elliptical mirror, the pulse laser beam and the IR CW laser beam are concentrated on the chamber by the elliptical mirror, and the first dichroic mirror and the second dichroic mirror reflect or transmit light according to a wavelength, so that input light beams incident on the chamber are synthesized and an output light beam from the chamber is separated from the input light beams.

In some embodiments, the chamber has no electrodes therein.

In some embodiments, the uniformizing device includes a neutral density (ND) filter disposed between the plasma light source and the homogenizer and configured to gradually reduce the transmittance of the plasma light toward a central area of a cross section perpendicular to a traveling direction of the plasma light.

In some embodiments, the uniformizing device is a reflection structure that includes a combination of an elliptical mirror and a spherical mirror and reflects the plasma light in one direction, the elliptical mirror has a structure that is opened in a direction of the homogenizer, the spherical mirror is opened in a first direction and a second direction, the first direction being directed toward the elliptical mirror and the second direction being directed toward the homogenizer, and the reflection structure is configured such that an opened portion of the spherical mirror in the first direction is coupled to an opened portion of the elliptical mirror.

In some embodiments, the spherical mirror is configured to reflect the plasma light, which is not reflected by the elliptical mirror, toward the elliptical mirror, and the spherical mirror is configured to homogenize the intensity of the plasma light in a central area and the intensity of the plasma light in an outer peripheral area on a cross section perpendicular to a traveling direction of the plasma light.

In some embodiments, the uniformizing device includes: a reflection structure that includes a combination of an elliptical mirror and a spherical mirror and reflects the plasma light in one direction; and a neutral density (ND) filter disposed between the reflection structure and the homogenizer and configured to gradually reduce the trans-

mittance of the plasma light toward a central area of a cross section perpendicular to a traveling direction of the plasma light.

In some embodiments, the first optical system includes: a collimation lens configured to collimate light output from the homogenizer into parallel light; and an objective lens configured to irradiate the parallel light on the inspection object and receive light reflected from the inspection object, and the inspection apparatus further comprises a beam splitter disposed between the collimation lens and the objective lens or between the homogenizer and the collimation lens to split the light irradiated on the inspection object and the light reflected from the inspection object.

According to some embodiments of the inventive concept, an inspection apparatus includes a plasma light source including a first dichroic mirror configured to transmit or reflect a pulse laser beam and reflect or transmit an infrared ray (IR) continuous wave (CW) laser beam; a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and discharge plasma light generated by the plasma; and a second dichroic mirror configured to transmit or reflect the pulse laser beam and the IR CW laser beam and reflect the plasma light; a first optical system configured to transfer plasma light to an inspection object; and a second optical system comprising an optical detector configured to detect light reflected from the inspection object.

In some embodiments, the chamber is surrounded by an elliptical mirror and is disposed at a focus of the elliptical mirror, the pulse laser beam and the IR CW laser beam are concentrated on the chamber by the elliptical mirror, and the first dichroic mirror and the second dichroic mirror reflect or transmit light according to a wavelength, so that input light beams incident on the chamber are synthesized and an output light beam from the chamber is separated from the input light beams.

In some embodiments, the chamber has no electrodes therein.

In some embodiments, the inspection apparatus further includes a uniformizing device including a neutral density (ND) filter disposed between the plasma light source and the first optical system and configured to gradually reduce the transmittance of the plasma light toward a central area of a cross section perpendicular to a traveling direction of the plasma light. In some embodiments, the uniformizing device is a reflection structure that includes a combination of an elliptical mirror and a spherical mirror and reflects the plasma light in one direction, the elliptical mirror has a structure that is opened in a direction of the homogenizer, the spherical mirror is opened in a first direction and a second direction, the first direction being directed toward the elliptical mirror and the second direction being directed toward the homogenizer, and the reflection structure is configured such that an opened portion of the spherical mirror in the first direction is coupled to an opened portion of the elliptical mirror. In some embodiments, the spherical mirror is configured to reflect the plasma light, which is not reflected by the elliptical mirror, toward the elliptical mirror, and the spherical mirror is configured to homogenize the intensity of the plasma light in a central area and the intensity of the plasma light in an outer peripheral area on a cross section perpendicular to a traveling direction of the plasma light.

In some embodiments, the inspection apparatus further includes a uniformizing device including a reflection structure that includes a combination of an elliptical mirror and a spherical mirror and reflects the plasma light in one

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direction; and a neutral density (ND) filter disposed between the reflection structure and the first optical system and configured to gradually reduce the transmittance of the plasma light toward a central area of a cross section perpendicular to a traveling direction of the plasma light. In some embodiments, the first optical system includes: a collimation lens configured to collimate light output from the homogenizer into parallel light; and an objective lens configured to irradiate the parallel light on the inspection object and receive light reflected from the inspection object, and the inspection apparatus further comprises a beam splitter disposed between the collimation lens and the objective lens or between the homogenizer and the collimation lens to split the light irradiated on the inspection object and the light reflected from the inspection object.

BRIEF DESCRIPTION OF THE DRAWINGS

Example embodiments of the inventive concept will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings in which:

FIGS. 1A and 1B are schematic diagrams of a plasma light source according to example embodiments of the inventive concept;

FIG. 2 is a schematic diagram illustrating light passing through a pair of axicon lenses in the plasma light source of FIG. 1A;

FIGS. 3 to 8 are schematic diagrams of plasma light sources according to example embodiments of the inventive concept;

FIG. 9 is a schematic diagram of an inspection apparatus including an illumination optical system according to example embodiments of the inventive concept;

FIG. 10 is a schematic diagram illustrating transmittance according to a position of a neutral density filter employed in the inspection apparatus of FIG. 9;

FIG. 11A is a simulation image of a light intensity distribution when the neutral density filter is omitted from the inspection apparatus of FIG. 9, and FIG. 11B is a simulation image of a light intensity distribution when the neutral density filter is present in the inspection apparatus of FIG. 9;

FIGS. 12A and 12B are graphs of the light intensity distributions in an x slice and a y slice correspond to the images of FIGS. 11A and 11B, respectively;

FIGS. 13 to 15 are schematic diagrams of inspection apparatuses including an illumination optical system, according to example embodiments of the inventive concept;

FIG. 16 is a schematic diagram of an inspection apparatus including an illumination optical system, according to another example embodiment of the inventive concept;

FIGS. 17 to 19 are diagrams illustrating the configuration and function of a reflection structure employed in the inspection apparatus of FIG. 16;

FIG. 20A is a simulation image of a light intensity distribution when only an elliptical mirror is present in the inspection apparatus of FIG. 16, and FIG. 20B is a simulation image of a light intensity distribution when a reflection structure including a spherical mirror is present in the inspection apparatus of FIG. 16;

FIGS. 21A and 21B are graphs of light intensity distributions in an x slice and a y slice corresponding to the images of FIGS. 20A and 20B, respectively; and

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FIGS. 22 to 24 are schematic diagrams of inspection apparatuses including an illumination optical system, according to example embodiments of the inventive concept.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Hereinafter, example embodiments of the inventive concept will be described with reference to the accompanying drawings. The inventive concept may, however, be embodied in many different forms and should not be construed as being limited to the example embodiments set forth herein; rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the inventive concept to those of ordinary skill in the art. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

It will be understood that when an element, such as a layer, a region, or a substrate, is referred to as being “on” or “connected to” another element, it may be directly on, connected or coupled to the other element or intervening elements may be present. In the drawings, the dimensions of structures are exaggerated for clarity of the inventive concept. Parts having no relation to the description are omitted. Like reference numerals denote like elements throughout the specification and drawings. The terminology used herein is for the purpose of describing particular example embodiments only and is not intended to be limiting of the inventive concept.

FIGS. 1A and 1B are schematic diagrams of a plasma light source **100** according to an example embodiment of the inventive concept. FIG. 1A illustrates a process of inputting an infrared ray continuous wave (CW) laser beam and a pulse laser beam to a chamber **130**, and FIG. 1B illustrates a process of outputting plasma light from the chamber **130**. FIG. 2 is a schematic diagram of light passing through a pair of axicon lenses in the plasma light source **100** of FIGS. 1A and 1B.

Referring to FIGS. 1A and 1B, the plasma light source **100** according to example embodiments may include a pulse laser generator **110**, a CW laser generator **120**, the chamber **130**, first and second dichroic mirrors **140** and **150**, and an elliptical mirror **160**. In addition, the plasma light source **100** may further include a first input optical system **170** configured to input a pulse laser beam to the first dichroic mirror **140**, and a second input optical system **180** configured to input a CW laser beam to the second dichroic mirror **150**.

The pulse laser generator **110** may generate a pulse laser beam, for example, a visible ray pulse laser beam, and input the pulse laser beam to the chamber **130**. The pulse laser beam, which is generated by the pulse laser generator **110**, is not limited to a visible ray pulse laser beam. For example, the pulse laser beam, which is generated by the pulse laser generator **110**, may have various wavelengths, such as infrared rays or ultraviolet rays.

On the other hand, the pulse laser beam, which is generated by the pulse laser generator **110**, may have very high peak power. For example, the pulse laser beam may have sufficient peak power to ignite plasma in the chamber **130**. In addition, since the pulse laser beam is used only for plasma ignition, the time taken to input the pulse laser beam to the chamber **130** may be short and the average power of the pulse laser beam may be low. Therefore, light emission of the plasma ignited by the pulse laser beam may be weak.

During a predetermined period of time after the plasma ignition, the pulse laser beam may be continuously input to the chamber 130.

The pulse laser beam may be converted into a ring-shaped beam through the first input optical system 170 and be input to the elliptical mirror 160 by the reflection of the first dichroic mirror 140 and the transmission of the second dichroic mirror 150. Since the pulse laser beam is input to the chamber 130 by the reflection of the elliptical mirror 160 and is concentrated, the pulse laser beam is capable of igniting plasma. The configurations and functions of the first dichroic mirror 140, the second dichroic mirror 150, and the elliptical mirror 160 are described below in more detail.

The CW laser generator 120 may generate a CW laser beam, for example, an infrared ray (IR) CW laser beam, and input the CW laser beam to the chamber 130. The CW laser beam, which is generated by the CW laser generator 120, is not limited to an IR CW laser beam.

The CW laser beam, which is generated by the CW laser generator 120, may be input to the chamber 130 so as to maintain the plasma in an ignited state and to increase the ignited plasma to high power. Accordingly, the CW laser beam may be, for example, a high-power CW laser beam having sufficient energy to maintain the plasma in an ignited state and increase the intensity of plasma.

The CW laser beam may be converted into a ring-shaped beam through the second input optical system 180, pass through the first dichroic mirror 140 and the second dichroic mirror 150, and be input to the elliptical mirror 160. Since the CW laser beam is input to the chamber 130 by the reflection of the elliptical mirror 160 and is concentrated, the CW laser beam may contribute to maintaining the plasma in an ignited state and increasing the intensity of the plasma. On the other hand, the pulse laser beam and the CW laser beam are concentrated and superimposed at the same converging point, for example, a focus of the elliptical mirror 160, in the chamber 130 by the reflection of the elliptical mirror 160. Thus, high-power plasma may be generated. After the generation of the high-power plasma, the high-power plasma may be maintained even when the pulse laser beam is interrupted.

The pulse laser generator 110 and the CW laser generator 120 may include collimation lenses, respectively, so as to output the pulse laser beam and the CW laser beam as parallel light.

The chamber 130 or a lamp may accommodate a medium material for plasma ignition. That is, the chamber 130 may airtightly accommodate a medium material for plasma ignition in a solid, liquid, or gas state at an early stage. The medium material for plasma ignition may also be referred to as an ionizable medium material. The chamber 130 may be supported by a support (not illustrated) and be fixed to the elliptical mirror 160. For example, the chamber 130 may be supported by the support connected to a portion that does not contribute to the reflection of the elliptical mirror 160 and be fixed to the focus of the elliptical mirror 160. More specifically, the chamber 130 may be fixed to the elliptical mirror 160 such that the converging point in the chamber 130 matches the focus of the elliptical mirror 160.

The chamber 130 may be made of at least one selected from the group consisting of a dielectric material, a quartz material, suprasil quartz, sapphire, magnesium fluoride (MgF_2), diamond, and calcium fluoride (CaF_2). The material of the chamber 130 may be appropriately selected by taking into account the medium material for plasma ignition to be accommodated in the chamber 130 and/or plasma light at a wavelength to be generated and output by the chamber 130.

In the present example embodiment, the chamber 130 may be made of a material that is transparent to a pulse laser beam, a CW laser beam, and ultraviolet (UV) rays. Accordingly, the chamber 130 may discharge plasma light corresponding to the UV rays among the generated plasma light beams.

The chamber 130 may accommodate various medium materials for plasma ignition. For example, the medium material for plasma ignition may be at least one selected from the group consisting of a noble gas, xenon (Xe), argon (Ar), neon (Ne), krypton (Kr), helium (He), deuterium (D_2), hydrogen (H_2), oxygen (O_2), fluorine (F_2), metal halide, mercury (Hg), cadmium (Cd), zinc (Zn), tin (Sn), gallium (Ga), iron (Fe), lithium (Li), sodium (Na), excimer-forming gas, air, steam, metal oxide, aerosol, a fluid medium, and a regenerating medium.

However, the medium material for plasma ignition is not limited thereto. The medium material for plasma ignition may be generated by using a solid or liquid target (not illustrated) (hereinafter referred to as "target") formed within the chamber 130. For example, the medium material for plasma ignition may be generated by irradiating a laser beam on the target formed within the chamber 130. The target may be a metal pool or a metal film. The target may be a solid or a liquid that is movable within the chamber 130. For example, the target may be a droplet that is movable within the chamber 130.

The medium material for plasma ignition may be a material that is introduced into the chamber 130 and is used to ignite plasma, or may be a material that may easily ignite plasma by using a pulse laser beam, for example, a visible ray pulse laser beam. When the plasma is ignited, high-power energy is supplied to the chamber 130 by the CW laser beam, for example, the IR CW laser beam, thus maintaining the intensity of plasma and maximizing the intensity of plasma.

In the plasma light source 100 according to the present example embodiment, since the plasma ignition is performed by using a pulse laser beam, no electrodes may exist within the chamber 130. Therefore, the plasma light source 100 according to the present example embodiment may be a plasma light source employing an electrodeless lamp or an electrodeless chamber.

The first dichroic mirror 140 may reflect the pulse laser beam input from the pulse laser generator 110 toward the elliptical mirror 160, and may transmit the CW laser beam input from the CW laser generator 120 toward the elliptical mirror 160. The first dichroic mirror 140 is disposed in a direction in which the laser beams of the pulse laser generator 110 and the CW laser generator 120 are emitted. The first dichroic mirror 140 may be disposed such that the pulse laser generator 110 and the CW laser generator 120 maintain a predetermined angle. For example, the pulse laser generator 110 and the CW laser generator 120 may be disposed to maintain substantially 90° with respect to an apex of the first dichroic mirror 140. In addition, the first dichroic mirror 140 may be disposed to have a slope of substantially 45° with respect to traveling directions of the pulse laser beam and the CW laser beam. On the other hand, the arrangement angles of the pulse laser generator 110 and the CW laser generator 120 may be changed. In this case, the slope of the first dichroic mirror 140 may be changed.

The second dichroic mirror 150 may be disposed between the first dichroic mirror 140 and the elliptical mirror 160 and may transmit both the pulse laser beam and the CW laser beam toward the elliptical mirror 160. In addition, the second dichroic mirror 150 may reflect the plasma light

discharged from the chamber **130** such that the plasma light is directed toward a homogenizer **240** such as a glass rod lens. More specifically, the plasma light corresponding to the UV rays may be discharged from the chamber **130** and be directly directed toward the homogenizer **240** by the reflection of the second dichroic mirror **150**, or may be reflected by the elliptical mirror **160** and then be directed toward the homogenizer **240** by the reflection of the second dichroic mirror **150**. The homogenizer **240** may be an optical mechanism that spatially homogenizes light and may not be included as an element of the plasma light source **100** according to the present example embodiment.

On the other hand, the homogenizer **240** may be disposed to substantially be 90° with respect to the elliptical mirror **160**, with the second dichroic mirror **150** as an apex. The second dichroic mirror **150** may be disposed to have a slope of substantially 45° with respect to traveling directions of the pulse laser beam, the CW laser beam, and the plasma light, based on reflection and transmission characteristics. The arrangement angle of the homogenizer **240** may be changed. In this case, the slope of the second dichroic mirror **150** may be changed.

The dichroic mirror is a mirror configured by a combination of a plurality of thin films made of materials having different refractive indexes. The dichroic mirror reflects light of a predetermined wavelength and transmits light of the other wavelengths. As compared with a general color filter, the dichroic mirror has very low absorption loss, and a wavelength range of light selectively reflected may be increased or decreased according to a material thickness or a structure of the dichroic mirror.

In the plasma light source **100** according to the present example embodiment, the first dichroic mirror **140** and the second dichroic mirror **150** may be disposed on the same axis with respect to the three kinds of light, for example, the pulse laser beam, the CW laser beam, and the plasma light. In the case of the pulse laser beam, the same axis may be a concept based on the light that is directed toward the elliptical mirror **160** by the reflection of the first dichroic mirror **140**, and in the case of the plasma light, the same axis may be a concept based on the light that is directed from the elliptical mirror **160** to the second dichroic mirror **150**.

By selectively reflecting or transmitting the light according to a wavelength through the two dichroic mirrors, namely, the first and second dichroic mirrors **140** and **150**, which are disposed on the same axis, input light beams incident on the chamber **130** may be combined or synthesized and an output light beam output from the chamber **130** may be separated from the incident input lights. Specifically, the pulse laser beam and the CW laser beam may be input to the chamber **130** through the two dichroic mirrors, namely, the first and second dichroic mirrors **140** and **150**, and be synthesized. In addition the plasma light, which is generated in the chamber **130**, may be separated from the pulse laser beam and the CW laser beam and be output to the homogenizer **240**. Since the plasma light source **100** according to the present example embodiment is configured to input and output light beams through the two dichroic mirrors, namely, the first and second dichroic mirrors **140** and **150**, disposed on the same axis, the plasma light source **100** may have a very simple configuration without movement of devices.

The elliptical mirror **160** is configured to surround the chamber **130** and may have a structure that is opened toward the dichroic mirrors **140** and **150**. The elliptical mirror **160** may reflect most electromagnetic waves. For example, the

elliptical mirror **160** may reflect plasma light corresponding to the pulse laser beam, the CW laser beam, and the UV rays.

The elliptical mirror **160** may have the following law of reflection: That is, light, which is output from one focus of the elliptical mirror **160**, is reflected by the elliptical mirror and travels to another focus of the elliptical mirror **160**. Accordingly, in a case where the converging point in the chamber **130** is identical to a first focus F1, which is one focus of the elliptical mirror **160**, the light incident from a second focus F2, which is another focus of the elliptical mirror **160**, is collected at the converging point corresponding to the first focus F1 by the reflection of the elliptical mirror **160**, and the light discharged from the converging point travels to the second focus F2 by the reflection of the elliptical mirror **160**. For reference, the pulse laser beam input by the reflection of the first dichroic mirror **140** may be regarded as light output from the second focus F2 in terms of the elliptical mirror **160**. In practice, the plasma light output by the reflection of the elliptical mirror **160** is also bent by the reflection of the second dichroic mirror **150**, but the plasma light may be regarded as traveling toward the second focus F2 in terms of the elliptical mirror **160**.

Since the plasma light source **100** according to the present example embodiment employs the elliptical mirror **160**, it is possible to maximize the light concentration efficiency of the input light beams, for example, the pulse laser beam and the CW laser beam, in the chamber **130**. In addition, it is possible to maximize the output efficiency of the plasma light discharged from the chamber **130** through the elliptical mirror **160**.

The first input optical system **170** is an optical system configured to input the pulse laser beam from the pulse laser generator **110** to the first dichroic mirror **140** and may include a pair of axicon lenses **171** and a concave lens **173**. The pair of axicon lenses **171** may convert the pulse laser beam into a ring-shaped beam. As illustrated in FIG. 2, the ring-shaped beam means a beam that is distributed in a donut shape or a circular-ring shape on a cross section perpendicular to a traveling direction of light. The ring-shaped beam may be formed using elements other than axicon lenses, for example, a spatial light modulator (SLM).

The concave lens **173** may expand the incident light. For example, when the ring-shaped beam is incident on the concave lens **173**, an internal radius (R1 of FIG. 2), an external radius (R2 of FIG. 2), and a width (W1 of FIG. 2) may be expanded. That is, the first input optical system **170** may convert the pulse laser beam into the ring-shaped beam, expand the ring-shaped beam, and input the expanded ring-shaped beam to the first dichroic mirror **140**.

For reference, if the pulse laser beam is concentrated, plasma may be generated even in the atmosphere. This is because media for plasma ignition, such as oxygen, nitrogen, and water, exist in the atmosphere. Therefore, by employing the concave lens **173**, it is possible to reduce or prevent the generation of plasma in the atmosphere.

In addition, the concave lens **173** may make light appear as if the light is expanded from one point. Accordingly, it may appear as if the pulse laser beam is output from the second focus F2 of the elliptical mirror **160** through the concave lens **173** and the first dichroic mirror **140**. As described above, the light output from the second focus F2 travels toward the first focus F1 corresponding to the converging point by the reflection of the elliptical mirror **160**. Therefore, the ring-shaped pulse laser beam passing through the concave lens **173** may be concentrated on the converging point of the chamber **130** by the reflection of the elliptical mirror **160**.

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The second input optical system **180** is an optical system configured to input the CW laser beam from the CW laser generator **120** to the first dichroic mirror **140** and may include a pair of axicon lenses **181**, a convex lens **183**, and a cylindrical lens **185**. As in the first input optical system **170**, the pair of axicon lenses **181** may convert the CW laser beam into a ring-shaped beam.

The convex lens **183** may concentrate the incident light. For example, in a case where the ring-shaped beam is input to the convex lens **183**, the ring-shaped beam may be contracted to substantially a point. On the other hand, after the incident light is concentrated on the second focus F2 of the elliptical mirror **160**, the convex lens **183** makes the incident light be continuously directed toward the elliptical mirror **160**. Therefore, the ring-shaped CW laser beam passing through the convex lens **183** may be concentrated on the converging point of the chamber **130** by the reflection of the elliptical mirror **160**.

In the case of the CW laser beam input by the second input optical system **180**, for example, in the case of the IR CW laser beam, aberration may occur while the CW laser beam is passing through the first dichroic mirror **140** and the second dichroic mirror **150**. The cylindrical lens **185** may be disposed so as to correct such aberration. On the other hand, in the case of the pulse laser beam input through the first input optical system **170**, aberration may also occur. However, in the case of the pulse laser beam, the cylindrical lens need not be employed because the pulse laser beam is temporarily input for plasma ignition.

The process of generating the plasma light in the plasma light source **100** according to the present example embodiment will be described briefly.

As indicated by a thick arrow of FIG. 1A, the pulse laser beam from the pulse laser generator **110** is converted into the ring-shaped beam through the pair of axicon lenses **171**, is expanded through the concave lens **173**, and is input to the first dichroic mirror **140**. Subsequently, the pulse laser beam is reflected by the first dichroic mirror **140**, passes through the second dichroic mirror **150**, and is input to the elliptical mirror **160**. After that, the pulse laser beam is input to the chamber **130** by the reflection of the elliptical mirror **160**, is concentrated on the converging point, and ignites the plasma.

Thereafter, the CW laser beam from the CW laser generator **120** is converted into the ring-shaped beam through the pair of axicon lenses **181**, is concentrated through the convex lens **183**, and is input to the first dichroic mirror **140** through the cylindrical lens **185**. Subsequently, the CW laser beam passes through the first dichroic mirror **140** and the second dichroic mirror **150** and is input to the elliptical mirror **160**. After that, the CW laser beam is input to the chamber **130** by the reflection of the elliptical mirror **160**, is concentrated on the converging point, maintains the plasma in an ignited state, and increases the intensity of the plasma. After maintaining the plasma and increasing the intensity of the plasma, the input of the pulse laser beam may be stopped.

On the other hand, as indicated by a solid arrow of FIG. 1B, the plasma light (e.g., UV rays) generated by the plasma in the chamber **130** is discharged to the outside of the chamber **130** and is input to the second dichroic mirror **150** by the reflection of the elliptical mirror **160**. After that, the plasma light is reflected by the second dichroic mirror **150** and is input to the homogenizer **240**. On the other hand, some of the plasma light discharged to the outside may be directly input to the second dichroic mirror **150** without

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reflection of the elliptical mirror **160** and be input to the homogenizer **240** by the reflection of the second dichroic mirror **150**.

In the plasma light source **100** according to the present example embodiment, separate electrodes need not exist in the chamber **130** because the pulse laser beam is used to ignite the plasma and the CW laser beam is used to maintain the plasma in an ignited state and increase the intensity of the plasma. Accordingly, in the plasma light source **100** according to the present example embodiment, it is unnecessary to connect electrodes at the time of replacing the chamber **130** and it is also unnecessary to readjust the position of the chamber **130** because the light-emitting point is not dependent on the position of the chamber **130**. Furthermore, since metal parts do not exist in the chamber **130**, the lifetime of the chamber **130** may be prolonged.

In addition, by reflecting or transmitting the light according to a wavelength through the two dichroic mirrors, namely, the first and second dichroic mirrors **140** and **150**, which are disposed on the same axis, the plasma light source **100** according to the present example embodiment may synthesize input light beams incident on the chamber **130** and separate an output light beam, which is output from the chamber **130**, from the incident input lights. Accordingly, the plasma light source **100** according to the present example embodiment may have a simple structure without movement of devices, thus reducing manufacturing costs.

Furthermore, since the plasma light source **100** according to the present example embodiment employs the elliptical mirror **160**, it is possible to maximize light concentration efficiency of the input light beams, for example, the pulse laser beam and the CW laser beam, in the chamber **130**. In addition, it is possible to maximize the output efficiency of the plasma light discharged from the chamber **130** through the elliptical mirror **160**.

The plasma light source **100** according to the present example embodiment may be used in an inspection apparatus or a microscope configured to inspect a wafer, a semiconductor package, a semiconductor chip, or a display panel during a semiconductor manufacturing process. In addition, the plasma light source **100** according to the present example embodiment may be used as a light source in an exposure process.

FIGS. 3 to 8 are schematic diagrams of plasma light sources **100a** to **100f** according to example embodiments of the inventive concept. For convenience, the description provided above with reference to FIGS. 1A and 1B will not be repeated again.

Referring to FIG. 3, the plasma light source **100a** according to the present example embodiment may differ from the plasma light source **100** of FIG. 1A in terms of an arrangement angle of a second dichroic mirror **150a**. Specifically, in the plasma light source **100a** according to the present example embodiment, the second dichroic mirror **150a** may be disposed to reflect plasma light in a downward direction. Accordingly, in order to receive the plasma light reflected from the second dichroic mirror **150a**, a homogenizer **240** may be disposed under the second dichroic mirror **150a**, as illustrated in FIG. 3.

As illustrated in FIG. 3, an inclination direction of the second dichroic mirror **150a** may be identical to an inclination direction of the first dichroic mirror **140**. In addition, the inclination angle of the second dichroic mirror **150a** may be identical to or different from the inclination angle of the first dichroic mirror **140**. As described above, the inclination angles of the first dichroic mirror **140** and the second

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dichroic mirror **150a** may be changed according to the arrangement positions of the pulse laser generator **110** and the homogenizer **240**.

Referring to FIG. 4, the plasma light source **100b** according to the present example embodiment differs from the plasma light source **100** of FIG. 1A in that a pulse laser generator **110** and a first input optical system **170** change positions thereof with those of a CW laser generator **120** and a second input optical system **180**, respectively. Specifically, the pulse laser generator **110** and the first input optical system **170** may be disposed on a left front side of a first dichroic mirror **140a**, and the CW laser generator **120** and the second input optical system **180** may be disposed under the first dichroic mirror **140a**.

On the other hand, due to the change in positions, reflection and transmission characteristics of the first dichroic mirror **140a** may also be changed. For example, the first dichroic mirror **140a** may transmit the pulse laser beam, for example, the visible ray pulse laser beam, and direct the pulse laser beam toward the second dichroic mirror **150**. In addition, the first dichroic mirror **140a** may reflect the CW laser beam, for example, the IR CW laser beam, and direct the CW laser beam toward the second dichroic mirror **150**.

In other words, the arrangement positions of the pulse laser generator **110** and the CW laser generator **120** may be changed according to the reflection and transmission characteristics of the first dichroic mirror **140a**. Furthermore, as the arrangement positions of the pulse laser generator **110** and the CW laser generator **120** are changed, the arrangement positions of the first input optical system **170** and the second input optical system **180** may also be changed. The configurations and functions of the first input optical system **170** and the second input optical system **180** are the same as those described above with reference to FIGS. 1A and 1B.

Referring to FIG. 5, the plasma light source **100c** according to the present example embodiment may differ from the plasma light source **100** of FIG. 1A in terms of an input structure of a pulse laser beam and a configuration of dichroic mirrors.

Specifically, in the plasma light source **100c** according to the present example embodiment, the pulse laser beam from the pulse laser generator **110** disposed on a right rear side of the elliptical mirror **160a** may be directly input to the chamber **130** through the convex lens **183**. In order to directly input the pulse laser beam to the chamber **130**, a transmission area **At** such as a lens or a window capable of transmitting the pulse laser beam may be formed in the elliptical mirror **160a**. In some cases, the transmission area **At** may have a through-hole shape without separate material layers. The pulse laser beam may be concentrated on the converging point of the chamber **130** by the convex lens **183**. Therefore, the pulse laser beam may ignite the plasma in the chamber **130** as in the plasma light source **100** of FIG. 1A.

In addition, in the plasma light source **100c** according to the present example embodiment, only the second dichroic mirror **150a** may be included and the first dichroic mirror **140** may be omitted. In other words, the main function of the first dichroic mirror **140** is to input the pulse laser beam. In the plasma light source **100c** according to the present example embodiment, the first dichroic mirror may need not exist because the pulse laser beam is directly input from the rear of the elliptical mirror **160a**.

The CW laser beam from the CW laser generator **120** is input to the second dichroic mirror **150** through the second input optical system **180**, passes through the second dichroic mirror **150**, and is reflected by the elliptical mirror **160a**. Thus, the CW laser beam may be concentrated on the

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converging point of the chamber **130**, maintain the plasma in an ignited state, and increase the intensity of the plasma. On the other hand, as in the plasma light source **100** of FIG. 1A, the plasma light discharged from the chamber **130** may be input to the homogenizer **240** by the reflection of the elliptical mirror **160a** and the reflection of the second dichroic mirror **150**.

Referring to FIG. 6, the plasma light source **100d** according to the present example embodiment may differ from the plasma light source **100c** of FIG. 5 in that a CW laser beam is input to a chamber **130** by the reflection of a first dichroic mirror **140a**. Specifically, similar to the plasma light source **100c** of FIG. 5, the plasma light source **100d** according to the example embodiment may be configured such that a pulse laser beam is directly input to a right rear side of an elliptical mirror **160a**. However, the plasma light source **100d** according to the present example embodiment may further include the first dichroic mirror **140a** disposed on a left front side of a second dichroic mirror **150**, and the CW laser beam may be input to the chamber **130** by the reflection of the first dichroic mirror **140a**.

In other words, the CW laser beam from the CW laser generator **120** is input to the first dichroic mirror **140a** through the second input optical system **180**, is reflected by the first dichroic mirror **140a**, and is input to the elliptical mirror **160a**. After that, the CW laser beam may be reflected by the elliptical mirror **160a**, is input to the chamber **130**, and be concentrated on the converging point of the chamber **130**.

Referring to FIG. 7, the plasma light source **100e** according to the present example embodiment may differ from the plasma light source **100c** of FIG. 5 in terms of reflection and transmission characteristics of a second dichroic mirror **150b**. For example, in the plasma light source **100e** according to the present example embodiment, the second dichroic mirror **150b** may have characteristics that transmit the plasma light (e.g., UV rays) and reflect the CW laser beam (e.g., IR CW laser beam). Accordingly, the CW laser generator **120** and the second input optical system **180** may be disposed above the second dichroic mirror **150b**, and the homogenizer **240** may be disposed on the left front side of the second dichroic mirror **150b**.

Specifically, the CW laser beam from the CW laser generator **120** may be input to the elliptical mirror **160a** by the reflection of the second dichroic mirror **150b** and be concentrated on the converging point of the chamber **130** by the reflection of the elliptical mirror **160a**. On the other hand, the plasma light (e.g., UV rays) discharged to the outside may be directed toward the second dichroic mirror **150b** by the reflection of the elliptical mirror **160a**, pass through the second dichroic mirror **150b**, and be input to the homogenizer **240**.

Referring to FIG. 8, the plasma light source **100f** according to the present example embodiment may differ from the plasma light source **100c** of FIG. 5 in that the pulse laser generator **110** changes a position thereof with that of a CW laser generator **120**.

In the plasma light source **100f** according to the present example embodiment, the pulse laser generator **110** and a first input optical system **170** may be disposed on a left front side of a second dichroic mirror **150**, and the CW laser generator **120** may be disposed on a right rear side of an elliptical mirror **160a**. Under such an arrangement configuration, the pulse laser beam from the pulse laser generator **110** is input to the second dichroic mirror **150** through the first input optical system **170**, passes through a second dichroic mirror **150**, and is input to the elliptical mirror

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160a. After that, the pulse laser beam is input to a chamber **130** by the reflection of the elliptical mirror **160a** and is concentrated on a converging point, and thus, the pulse laser beam is capable of igniting plasma.

On the other hand, the CW laser beam from the CW laser beam generator **120** is concentrated on the converging point of the chamber **130** through a transmission area **At** of the elliptical mirror **160a** by a convex lens **183**, thus maintaining the plasma in an ignited state and increasing the intensity of the plasma. In addition, as in the plasma light source **100c** of FIG. **5**, the plasma light discharged from the chamber **130** may be input to a homogenizer **240** by the reflection of the elliptical mirror **160a** and the reflection of the second dichroic mirror **150**.

FIG. **9** is a schematic diagram of an inspection apparatus **1000** including an illumination optical system, according to an example embodiment of the inventive concept.

Referring to FIG. **9**, the inspection apparatus **1000** according to the present example embodiment may include a light source **210**, an elliptical mirror **220**, a neutral density (ND) filter **230**, a homogenizer **240**, a first optical system **250**, a beam splitter **260**, a second optical system **1250**, and a detector **1200**. The inspection apparatus **1000** may be an apparatus for inspecting a wafer, a semiconductor package, a semiconductor chip, a display panel, or the like in a semiconductor manufacturing process. In addition, the inspection apparatus **1000** may be a microscope. The light source **210**, the elliptical mirror **220**, the ND filter **230**, the homogenizer **240**, the first optical system **250**, and the beam splitter **260** may correspond to an illumination optical system that irradiates light on an inspection object **3000**, and the second optical system **1250** and the detector **1200** may correspond to a detection optical system that detects light reflected from the inspection object **3000**.

The light source **210** may be a plasma light source. For example, as illustrated in FIG. **9**, the light source **210** may be a plasma light source including a short arc discharge lamp. However, the light source **210** according to the present example embodiment is not limited to a short arc discharge lamp. Examples of the light source **210** may include any types of plasma light sources that ignite plasma by using various ignition sources, such as microwaves, UV rays, high-frequency waves, a flash lamp, a pulse laser beam, or a pulse lamp. Furthermore, the light source **210** is not limited to a plasma light source and may include a laser beam light source or a light-emitting diode (LED) light source.

The light source **210** having the short arc lamp structure may include a chamber **211** in which a medium for plasma generation is sealed and plasma is ignited, a pair of electrodes **213** protruding inward from the chamber **211** so as to cause discharge in the chamber **211**, and a pair of legs **215** that supports the chamber **211** and provide an extension passage of the electrodes **213**.

The elliptical mirror **220** may be treated as an element of the light source **210** or may be treated as an element separate from the light source **210**. The elliptical mirror **220** may reflect light generated by the light source **210** and concentrate the reflected light on the homogenizer **240**.

On the other hand, when the light is concentrated by the elliptical mirror **220**, the spatial light intensity on an incidence surface of the homogenizer **240** may appear as a Gaussian distribution. If light having different spatial intensities is directly used as an illumination of a microscope or an inspection apparatus, a bright region and a dark region occur. A difference of brightness in these regions may cause a great problem in the microscope or the inspection apparatus. A spatial intensity distribution of light may be homog-

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enized in a relatively simple manner by passing the light through the homogenizer **240**. However, when passes through the homogenizer **240**, the light repeats only a total reflection therein. Hence, an incidence angle of the light to the homogenizer **240** is equal to an exit angle of the light from the homogenizer **240**. Therefore, the homogenizer **240** may not homogenize a light intensity distribution in terms of angle. The angle may mean an angle (e.g., a solid angle) that increases as a distance from a center of a concentric circle increases on a cross section perpendicular to a traveling direction of the light.

Due to the configuration of the elliptical mirror **220**, the intensity of reflected light around the hole of the center (arrow B) is highest and the intensity of light is gradually weaker toward an outer periphery (arrow A). Thus, it can be seen that the intensity of light is greatly dependent on the incidence angle of the light. Therefore, even when the light reflected from the elliptical mirror **220** passes through the homogenizer **240**, the light intensity distribution in terms of angle may be non-uniform.

The ND filter **230** may reduce the light transmittance as a distance to the center decreases. For example, when the light passes through the ND filter **230**, the light transmittance is low in the center and the light transmittance is high in the outer periphery. Therefore, if the light having high intensity in the center and low intensity in the outer periphery passes through the ND filter **230**, overall uniform light may be generated due to transmittance characteristics of the ND filter **230**.

The ND filter **230** is also called an ND gradient filter or a gradient ND filter. The function of the ND filter **230** is described below in more detail with reference to FIGS. **10** to **12**.

The homogenizer **240** may spatially homogenize the intensity of light through total reflection. However, due to the total reflection characteristic, the intensity of light may not be homogenized in terms of angle.

The first optical system **250** may include a collimation lens **252** and an objective lens **254**. The collimation lens **252** may convert light output from the homogenizer **240** into parallel light. The collimation lens **252** may have a tube lens shape. The objective lens **254** concentrates the parallel light from the collimation lens **252** and irradiates the concentrated parallel light on the inspection object **3000**.

The inspection object **3000** may be various devices to be inspected, such as a wafer, a semiconductor package, a semiconductor chip, and a display panel. The inspection object **3000** may be disposed and supported on an inspection stage (not illustrated) that is movable in x, y, and z directions.

The beam splitter **260** may transmit the parallel light from the collimation lens **252** and transfer the parallel light to the objective lens **254**. In addition, the beam splitter **260** may reflect the light, which is reflected from the inspection object **3000** and transferred through the objective lens **254**, and transfers the reflected light to the second optical system **1250**. The beam splitter **260** may be a type of dichroic mirror. On the other hand, the beam splitter **260** may reflect the parallel light from the collimation lens **252** and transmit the reflected light from the objective lens **254** according to reflection and transmission characteristics of the beam splitter **260**. In this case, the light source **210**, the elliptical mirror **220**, the ND filter **230**, and the collimation lens **252** may be disposed on the side of the beam splitter **260**, and the second optical system **1250** and the detector **1200** may be disposed above the beam splitter **260** so as to be on the same line as the inspection object **3000**.

The second optical system **1250** may transfer the reflected light received from the beam splitter **260** to the detector **1200**. The second optical system **1250** may be a relay lens.

The detector **1200** may receive the reflected light from the second optical system **1250** and transfer the reflected light to other analysis devices (not illustrated) for analyzing the reflected light. In some cases, the detector **1200** may include an analyzer or may interwork with an analyzer to analyze the reflected light. The detector **1200** may be a charge-coupled device (CCD) camera. The detector **1200** is not limited to a CCD camera and may adopt various sensors, including a complementary metal-oxide semiconductor (CMOS) image sensor.

By employing the ND filter **230**, the illumination optical system or the inspection apparatus according to the present example embodiment may homogenize the intensity distribution of the light reflected from the elliptical mirror **220** in terms of angle. Specifically, as described above, in the case of using the elliptical mirror **220**, the intensity of light is weak in the periphery, depending on the incidence angle. Thus, the light intensity distribution may be non-uniform in terms of angle. That is, the intensity of light may be high in the central area and low in the outer peripheral area on the cross section perpendicular to the traveling direction of the light. When the light having the above-described distribution passes through the ND filter **230**, the intensity of light is low in the central area due to the characteristics of the ND filter **230**. Thus, the light passing through the ND filter **230** may have a uniform light intensity distribution in terms of angle.

For reference, a method of using an optical fiber may be taken into account so as to improve the uniformity of the light intensity distribution in terms of angle. However, the optical fiber is usable only when the output of a visible ray range is low, and is difficult to use in the case of high-power UV rays. Since the UV rays have a low transmittance with respect to the optical fiber, optical loss is high. In addition, when the UV rays are incident, the optical fiber may be damaged. Hence, the optical fiber may not be used for high-brightness UV rays such as the plasma light.

FIG. **10** is a conceptual diagram for describing transmittance according to the position of the ND filter **230** employed in the inspection apparatus **1000** of FIG. **9**.

Referring to FIG. **10**, the ND filter **230** may have transmittance symmetrically varying about a center point C. For example, the ND filter **230** may be divided into a first area **A1** from the center point C to a first radius **R1**, a second area **A2** from an outer boundary of the first area **A1** to a second radius **R2**, a third area **A3** from an outer boundary of the second area **A2** to a third radius **R3**, and a fourth area **A4** from an outer boundary of the third area **A3** to a fourth radius **R4**. The first radius **R1**, the second radius **R2**, the third radius **R3**, and the fourth radius **R4** may be about 36 mm, about 48 mm, about 60 mm, and about 100 mm, respectively. In addition, the transmittance of the first area **A1**, the transmittance of the second area **A2**, the transmittance of the third area **A3**, and the transmittance of the fourth area **A4** may be about 35%, about 45%, about 60%, and about 98%, respectively. The area division of the ND filter **230** and the transmittance of each area are not limited to the above examples and may be variously changed.

When light having a uniform intensity distribution as a whole passes through the ND filter **230**, the transmitted light may have a light intensity distribution that gradually increases toward the outer periphery, that is, the fourth area **A4**. On the other hand, in the case of the light having a light intensity distribution that is high in the central area and low

in the outer peripheral area, if the light passes through the ND filter **230**, it is possible to obtain a uniform light intensity distribution as a whole. Therefore, angularly uniform light may be obtained by applying the ND filter **230** to angularly non-uniform light that is reflected by the elliptical mirror **220**.

FIG. **11A** is a simulation photograph of a light intensity distribution when the ND filter **230** is omitted from the inspection apparatus **1000** of FIG. **9**, and FIG. **11B** is a simulation photograph of a light intensity distribution when the ND filter **230** is present in the inspection apparatus **1000** of FIG. **9**. FIGS. **11A** and **11B** illustrate light intensity distributions on a pupil surface under the collimation lens **252** of the inspection apparatus **1000** of FIG. **9**.

Referring to FIG. **11A**, when the ND filter **230** is omitted, the intensity of light is gradually weaker as a distance increases from the central area to the outer peripheral area. However, as illustrated in FIG. **11B**, when the ND filter **230** is present, the intensity of light is uniform as a whole. A bright area has high intensity of light and a dark area has low intensity of light.

For reference, in the images of FIGS. **11A** and **11B**, no light is present in dark areas existing in the central area and the outer peripheral area, which may be caused by the configurations of the light source **210** and the elliptical mirror **220**. For example, as illustrated in FIG. **9**, when the light source **210** has a short arc discharge lamp structure, the portions corresponding to the legs **215** block the light, and thus, no light exists in the central area. In addition, only the light reflected by the elliptical mirror **220** is concentrated on the homogenizer **240**, and the remaining light is blocked. Thus, no light exists in the outer peripheral area corresponding to the outside of the elliptical mirror **220**.

FIGS. **12A** and **12B** are graphs of light intensity distributions in an X slice and a Y slice. The graphs of FIGS. **12A** and **12B** correspond to the images of FIGS. **11A** and **11B**, respectively.

Referring to FIG. **12A**, when the ND filter **230** is omitted, the intensity of light is gradually weaker as a distance increases from the central area to the outer peripheral area. However, as illustrated in FIG. **12B**, when the ND filter **230** is present, there is no great difference in the intensity of light between the central area and the outer peripheral area.

When numerically comparing the intensity of light in the graph of FIG. **12B** with the intensity of light in the graph of FIG. **12A**, the overall intensity of light in the graph of FIG. **12B** is similar to the intensity of light in the outer peripheral area of the graph of FIG. **12A**. As a result, the inspection apparatus **1000** according to the present example embodiment reduces the intensity of light in the central area by employing the ND filter **230**, thus homogenizing the overall intensity of light. The central area **Ac** having low intensity of light corresponds to the central area where no light exists in the images of FIGS. **11A** and **11B**.

FIGS. **13** to **15** are schematic diagrams of inspection apparatuses **1000a**, **1000b**, and **1000c** including an illumination optical system, according to example embodiments of the inventive concept. For convenience, the description provided above with reference to FIG. **9** will not be repeated again.

Referring to FIG. **13**, the inspection apparatus **1000a** according to the present example embodiment differs from the inspection apparatus **1000** of FIG. **9** in that a mirror **270** is further included and arrangements of elements are changed accordingly. Specifically, the mirror **270** may be disposed on a right rear side of an ND filter **230**, and a light source **210**, an elliptical source **220**, and the ND filter **230**

may be disposed on a left front side of the mirror **270**. The mirror **270** disposed as above may reflect light incident from the left side and direct the light in a downward direction. On the other hand, a homogenizer **240**, a first optical system **250**, and a beam splitter **260** may be disposed under the mirror **270**, and a second optical system **1250** and a detector **1200** may be disposed on a side of the beam splitter **260**.

By employing the mirror **270**, the inspection apparatus **1000a** according to the present example embodiment may increase the degree of freedom of space arrangement of elements, thus making the inspection apparatus **1000a** more compact.

Referring to FIG. **14**, the inspection apparatus **1000b** according to the present example embodiment differs from the inspection apparatus **1000** of FIG. **9** in terms of an arrangement position of a beam splitter **260**. The beam splitter **260** in the inspection apparatus **1000** of FIG. **9** is disposed between the collimation lens **252** and the objective lens **254**, but the beam splitter **260** in the inspection apparatus **1000b** of FIG. **14** may be disposed between a homogenizer **240** and a collimation lens **252**.

The beam splitter **260** simply separates light irradiated on an inspection object **3000** and light reflected from the inspection object **3000**. Thus, the inspection apparatus **1000b** may not be greatly influenced wherever the beam splitter **260** is disposed above or under the collimation lens **252**. The position of the second optical system **1250** and the detection **1200**, which receive the reflected light from the beam splitter **260**, may be also changed according to the arrangement position of the beam splitter **260**.

Referring to FIG. **15**, the inspection apparatus **1000c** according to the present example embodiment differs from the inspection apparatus **1000** of FIG. **9** in terms of a type of a light source **210a**. For example, the light source **210a** may have the same configuration as the plasma light source **100** described with reference to FIGS. **1A** and **1B**, instead of a short arc discharge lamp. More specifically, the light source **210a** may include a pulse laser generator **110**, a CW laser generator **120**, a chamber **130**, a first dichroic mirror **140**, a second dichroic mirror **150a**, an elliptical mirror **160**, a first input optical system **170**, and a second input optical system **180**.

A pulse laser beam (e.g., visible ray pulse laser beam) from the pulse laser generator **110** may be input to the chamber **130** and ignite plasma. A CW laser beam (e.g., IR CW laser beam) from the CW laser generator **120** may be input to the chamber **130**, maintain the plasma in an ignited state, and increase the intensity of plasma. Plasma light (e.g., UV rays) discharged from the chamber **130** may be reflected toward the second dichroic mirror **150a** by the elliptical mirror **160** and be reflected toward the ND filter **230** by the second dichroic mirror **150a**. Subsequent traveling processes of the output light may be substantially the same as those described above with reference to FIG. **9**.

Since the inspection apparatus **1000c** according to the present example embodiment includes the plasma light source **210a** having an electrodeless chamber structure and employs the ND filter **230**, it is possible to simplify the light source structure and homogenize the light intensity distribution in terms of angle.

In the inspection apparatus **1000c** according to the present example embodiment, the plasma light source **100** of FIGS. **1A** and **1B** is used as the light source **210a**, but any one of the plasma light sources **100a** to **100f** of FIGS. **3** to **8** may be used instead of the light source **100** of FIG. **1A**. In addition, in the inspection apparatus **1000c** according to the present example embodiment, the light source **210a** is not

limited to the plasma light sources **100** and **100a** to **100f** of FIGS. **1A** to **8**. For example, in the inspection apparatus **1000c** according to the example embodiment, examples of the light source **210a** may include a plasma light source using various ignition sources, such as microwaves, UV rays, high-frequency waves, a flash lamp, or a pulse lamp. In addition, the light source **210a** is not limited to a plasma light source and may be an LED light source or a laser beam light source.

In the inspection apparatus **1000c** according to the present example embodiment, the beam splitter **260** may be disposed between the homogenizer **240** and the collimation lens **252**, as in the inspection apparatus **1000b** of FIG. **14**. In addition, as in the inspection apparatus **1000a** of FIG. **13**, the inspection apparatus **1000c** according to the present example embodiment may improve spatial arrangement utilization of elements by employing the mirror **270**.

FIG. **16** is a schematic diagram of an inspection apparatus **2000** including an illumination optical system, according to another example embodiment of the inventive concept.

Referring to FIG. **16**, the inspection apparatus **2000** according to the present example embodiment may include a light source **310**, a reflection structure **320**, a homogenizer **340**, a first optical system **350**, a beam splitter **360**, a second optical system **2250**, and a detector **2200**. The light source **310**, the reflection structure **320**, the homogenizer **340**, the first optical system **350**, and the beam splitter **360** may correspond to an illumination optical system that irradiates light on an inspection object **3000**, and the second optical system **2250** and the detector **2200** may correspond to a detection optical system that detects light reflected from the inspection object **3000**.

The light source **310** may be a plasma light source. For example, as illustrated in FIG. **16**, the light source **310** may be a plasma light source including a short arc discharge lamp. Similar to the inspection apparatus **1000** of FIG. **9**, the light source **310** having the short arc discharge lamp structure may include a chamber **311**, a pair of electrodes **313**, and a pair of legs **315**. However, the light source **310** according to the present example embodiment is not limited to a short arc discharge lamp. Examples of the light source **310** may include any types of plasma light sources that ignite plasma by using various ignition sources, such as microwaves, UV rays, high-frequency waves, a flash lamp, a pulse laser beam, or a pulse lamp. Furthermore, the light source **310** is not limited to a plasma light source and may include a laser light source or an LED light source.

The reflection structure **320** may include an elliptical mirror **322** and a spherical mirror **324**. The reflection structure **320** may be treated as an element of the light source **310** or may be treated as an element separate from the light source **310**. The reflection structure **320** may reflect light generated by the light source **310** and may homogenize a light intensity distribution in terms of angle and concentrate the reflected light on the homogenizer **340**.

The elliptical mirror **322** may reflect light generated by the light source **310** and concentrate the reflected light on the homogenizer **340**. However, when the light is concentrated by the elliptical mirror **322** alone, the spatial intensity of light appears as a Gaussian distribution on the incidence surface of the homogenizer **340** and the spatial intensity of light may be homogenized by passing the light through the homogenizer **340**. However, as described above, the intensity of light may not be homogenized in terms of angle by the homogenizer **340** due to the total reflection characteristic of the homogenizer **340**.

On the other hand, due to the configuration of the elliptical mirror **322**, the intensity of reflected light around the hole of the center (arrow B) is highest and the intensity of light is gradually weaker toward the outer periphery (arrow A). Thus, as described above, the intensity of light is greatly dependent on the incidence angle of the light. By applying the elliptical mirror **322** to a microscope, an area where the numerical aperture (NA) is small may be brightly illuminated and an area where the NA is large may be darkly illuminated. In order to increase the resolution of the microscope, light needs to be irradiated uniformly at various angles. In a case of applying to an inspection apparatus, uniformity and higher brightness may be required.

For reference, the characteristics of the elliptical mirror **322** may be determined by the focus of the elliptical mirror **322**. For example, as illustrated in FIG. 16, assuming that the center of the chamber **311** is a first focus F1 of the elliptical mirror **322**, a distance from the elliptical mirror **322** is a first focal length FI1, an incidence surface of the homogenizer **340** is a second focus F2, and a distance from the elliptical mirror **322** is a second focal length FI2, the amount of light concentrated by the elliptical mirror **322** may increase as a ratio of FI2:FI1 increases. That is, when the ratio of FI2:FI1 increases, the first focus F1 is disposed at a much inner position of the elliptical mirror **322**, so that more light is reflected through the elliptical mirror **322**.

Due to the elliptical mirror **322**, the size of a spot concentrated on a converging point, that is, the second focus F2, increases by FI2/FI1 times. Therefore, as the ratio of FI2:FI1 increases, the size of the spot increases, causing a reduction in a coupling efficiency between the light and the homogenizer **240**. In addition, due to the configuration of the elliptical mirror **322**, the intensity of light reflected from the periphery is weak. Thus, the intensity of light is non-uniform according to angles, that is, the intensity of light is non-uniform in terms of angle. The angle may mean an angle (e.g., a solid angle) that increases as a distance from a center of a concentric circle increases on a cross section perpendicular to a traveling direction of the light.

On the contrary, as the ratio of FI2:FI1 decreases, a value of FI2/FI1 decreases and a small spot may be generated. Therefore, it is possible to increase a coupling efficiency between the light and the homogenizer **240** and to improve light intensity distribution uniformity according to angles. However, if the ratio of FI2:FI1 decreases, the amount of light concentrated by the elliptical mirror **322** is reduced as described above. Thus, light utilization efficiency may be reduced.

In order to solve the above-described problem of the elliptical mirror **322**, the inspection apparatus **2000** according to the present example embodiment employs the reflection structure **320** in which the spherical mirror **324** is combined with the elliptical mirror **322**. More specifically, in the reflection structure **320**, the elliptical mirror **322** has a structure that is opened in a direction of the homogenizer **340**, that is, a first direction (y direction), the spherical mirror **324** may have a structure that is opened in both directions while surrounding the opening of the elliptical mirror **322**. Accordingly, in the spherical mirror **324**, the first direction (y direction) may be directed toward the elliptical mirror **322** and a second direction (−y direction) may be directed toward the homogenizer **340**.

A first diameter (D1 of FIG. 18) of the opening of the spherical mirror **324** in the first direction may be greater than a second diameter (D2 of FIG. 18) of the opening of the spherical mirror **324** in the second direction. In addition, the first diameter (D1 of FIG. 18) of the opening of the spherical

mirror **324** may be greater than a third diameter (D3 of FIG. 18) of the opening of the elliptical mirror **321**. The second diameter (D2 of FIG. 18) of the opening of the spherical mirror **324** may be large enough to transmit the light reflected by the elliptical mirror **322** without being blocked. For example, the second diameter D2 of the spherical mirror **324** may be greater than the third diameter D3 of the elliptical mirror **322**.

A focal position of the elliptical mirror **322** may match a focal position of the spherical mirror **324**. In addition, the chamber **311** may be disposed at the same focus of the elliptical mirror **322** and the spherical mirror **324**. However, according to circumstances, the focal position of the elliptical mirror **322** may be different from the focal position of the spherical mirror **324**, and the chamber **311** may not be disposed at the same focus of the elliptical mirror **322** and the spherical mirror **324**.

In the reflection structure **320** having the above-described configuration, light deviating from the elliptical mirror **322** is reflected toward the elliptical mirror **322** by the spherical mirror **324**, and the elliptical mirror **322** reflects the light again and concentrates the light on the homogenizer **340**. Thus, it is possible to increase the amount of reflection light and increase light utilization efficiency. In addition, since the light returned by the spherical mirror **324** is reflected at the outer periphery of the elliptical mirror **322**, it is possible to increase the intensity of light at the outer periphery of the elliptical mirror **322**. Therefore, the reflection structure **320** may contribute to homogenization of the intensity of light in terms of angle. The configuration and function of the reflection structure **320** will be described in more detail with reference to FIGS. 17 to 19.

The homogenizer **340**, the first optical system **350**, the beam splitter **360**, the second beam splitter **1250**, and the detector **1200** are substantially identical to those of the inspection apparatus **1000** described above with reference to FIG. 9. As in the inspection apparatus **1000b** of FIG. 14, the beam splitter **360** may be disposed between the homogenizer **340** and the collimation lens **352**. In addition, as in the inspection apparatus **1000a** of FIG. 13, the inspection apparatus **2000** according to the present example embodiment may improve spatial arrangement utilization of elements by employing the mirror **270**.

Since the inspection apparatus **2000** according to the present example embodiment includes the reflection structure **320** having a combined structure of the elliptical mirror **322** and the spherical mirror **324**, more plasma light discharged from the chamber **311** is reflected and concentrated. Therefore, light utilization efficiency may be increased and the intensity of light at the periphery may be increased, thus homogenizing the light intensity distribution in terms of angle.

In the inspection apparatus **2000** according to the present example embodiment, due to the presence of the spherical mirror **324**, the reflection structure **320** may reflect a sufficient amount of light while using the elliptical mirror **322** having a small ratio of FI2:FI1. In addition, due to the use of the elliptical mirror **322** having a small ratio of FI2:FI1, the spot size of the converging point may be reduced and the brightness may be increased accordingly. As a result, the illumination optical system or the inspection apparatus **2000** according to the present example embodiment may construct an optical system that provides an angularly uniform light intensity distribution with higher brightness, as compared with an illumination optical system or an inspection apparatus using only an elliptical mirror.

FIGS. 17 to 19 are diagrams illustrating the configuration and function of the reflection structure employed in the inspection apparatus 2000 of FIG. 16.

Referring to FIGS. 17 to 19, the reflection structure 320 may be configured such that the opening of the elliptical mirror 322 is surrounded by one opening of the spherical mirror 324. In FIG. 17, for easy understanding, the light source 310 is not illustrated. In FIGS. 18 and 19, only the chamber 311 is illustrated and the other parts of the light source 310 are not illustrated.

On the other hand, a left small opening of the elliptical mirror 322 may be formed or not formed according to a type of the light source 310. For example, in a case where the plasma light source illustrated in FIG. 1A is used, the left opening of the elliptical mirror 322 may not be formed. In addition, since the left opening of the elliptical mirror 322 does not contribute to light reflection, the left opening of the elliptical mirror 322 may be formed, regardless of the type of the light source 310.

As described above, the focus of the elliptical mirror 322 may be equal to the focus of the spherical mirror 324, and the chamber 311 may be disposed at that focus. More specifically, the chamber 311 may be disposed such that the converging point of the chamber 311 matches the focus of the elliptical mirror 322 and the spherical mirror 324. In addition, as illustrated, the elliptical mirror 322 is combined with the spherical mirror 324 such that the cross section of the opening of the elliptical mirror 322 is on the same plane as the cross section of the left opening of the spherical mirror 324. However, according to circumstances, the cross section of the opening of the elliptical mirror 322 is not on the same plane as the cross section of the left opening of the spherical mirror 324. For example, since the elliptical mirror 322 is combined while being slightly shifted to the right, the cross section of the opening of the elliptical mirror 322 may be disposed inside of the spherical mirror 324 and the periphery thereof may partially overlap the spherical mirror 324 accordingly.

On the other hand, by adjusting a height H of the spherical mirror 324, it is possible to adjust a total amount of light reflected by the elliptical mirror 322. For example, if the height H of the spherical mirror 324 is reduced, the amount of light reflected by the spherical mirror 324 may be reduced and the amount of light reflected again by the elliptical mirror 322 may also be reduced accordingly. On the contrary, if the height H of the spherical mirror 324 is increased, the amount of light reflected by the spherical mirror 324 may be increased and the amount of light reflected again by the elliptical mirror 322 may also be increased accordingly.

In addition, by adjusting the height H of the spherical mirror 324, it is possible to adjust the intensity of light reflected from the periphery of the elliptical mirror 322. In other words, the area of the re-reflection portion of the elliptical mirror 322 may be changed according to the height H of the spherical mirror 324. More specifically, as illustrated in FIG. 18, the light reflected by the spherical mirror 324 passes through the focus thereof, is directed toward the elliptical mirror 322, and is reflected toward the homogenizer 340 by the elliptical mirror 322. On the other hand, light P1 reflected from a portion of the spherical mirror 324, adjacent to the elliptical mirror 322, may be re-reflected from an outer periphery of the elliptical mirror 322, and light P2 reflected from the outer periphery of the spherical mirror 324, disposed farther from the elliptical mirror 322, may be re-reflected from a much inner side of the elliptical mirror 322. Therefore, as the height H of the spherical mirror 324 increases, the re-reflection region of the elliptical mirror 322

may be widened, and as the height H of the spherical mirror 324 decreases, the re-reflection region of the elliptical mirror 322 may be narrowed. In addition, since the re-reflected light is added, the intensity of light is increased in the re-reflected region of the elliptical mirror 322. As a result, it is possible to adjust the intensity of light in the periphery of the elliptical mirror 322 by adjusting the height H of the spherical mirror 324.

FIG. 20A is a simulation photograph of a light intensity distribution when only the elliptical mirror 322 is present in the inspection apparatus 2000 of FIG. 16, and FIG. 20B is a simulation photograph of a light intensity distribution when a reflection structure including the spherical mirror 324 is present in the inspection apparatus 2000 of FIG. 16. FIGS. 20A and 20B illustrate light intensity distributions on a pupil surface under the collimation lens 252 of the inspection apparatus 2000 of FIG. 16.

Referring to FIG. 20A, when only the elliptical mirror 322 is present, the intensity of light is gradually weaker as a distance increases from the central area to the outer peripheral area. However, as illustrated in FIG. 20B, when the reflection structure 320, including the spherical mirror 324, is present, the intensity of light is uniform as a whole. This is because the light returned by the reflection of the spherical mirror 324 is re-reflected at the outer periphery of the elliptical mirror 322 and the intensity of light is increased at the outer periphery of the elliptical mirror 322. Similar to the images of FIGS. 11A and 11B, in the images of FIGS. 20A and 20B, no light is present in dark areas in the central area and the outer peripheral area because light is blocked by the configurations of the light source 310 and the elliptical mirror 322.

FIGS. 21A and 21B are graphs when cutting the light intensity distributions of FIGS. 20A and 20B into an x slice and a y slice, respectively. The graphs of FIGS. 21A and 21B correspond to the images of FIGS. 20A and 20B, respectively.

Referring to FIG. 21A, when only the elliptical mirror 322 is present, the intensity of light is gradually weaker as a distance increases from the central area to the outer peripheral area. However, as illustrated in FIG. 21B, when the reflection structure 320, including the spherical mirror 324, is present, there is no great difference in the intensity of light between the central area and the outer peripheral area.

When numerically comparing the intensity of light in the graph of FIG. 21B with the intensity of light in the graph of FIG. 21A, the overall intensity of light in the graph of FIG. 21B is similar to the intensity of light in the central area in the graph of FIG. 21A. As a result, the inspection apparatus 2000 according to the present example embodiment increases the intensity of light in the outer peripheral area by employing the reflection structure 320, thus homogenizing the overall intensity of light. The central area Ac having low intensity of light corresponds to the central area where no light exists in the images of FIGS. 20A and 20B.

More specifically, in the intensity of light in the graph of FIG. 21B, the intensity of light is gradually reduced from the central area to the outer peripheral area, is increased in the middle area, and is then reduced again. The middle area where the intensity of light is increased may be an interface between a re-reflection area of the elliptical mirror 322 and an inner area where no re-reflection occurs. That is, in the inner area where no re-reflection occurs, the intensity of light is reduced toward the outer peripheral area as in the case where only the elliptical mirror 322 is present. In the re-reflection area, light added by the reflection of the spherical mirror 324 is re-reflected. Thus, the intensity of light may

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be increased as much. On the other hand, when the distribution of the light added by the reflection of the spherical mirror **324** is uniform, the intensity of light may be gradually weaker toward the outer peripheral area even in the re-reflection area of the elliptical mirror **322**. However, the degree of weakening in the inner area or the re-reflection area may be very low, as compared with the case where only the elliptical mirror **322** is present.

FIGS. **22** to **24** are schematic diagrams of inspection apparatuses **2000a**, **2000b**, and **2000c** including an illumination optical system, according to example embodiments of the inventive concept.

Referring to FIG. **22**, the inspection apparatus **2000a** according to the present example embodiment differs from the inspection apparatus **2000** of FIG. **16** in terms of a type of a light source **310a**. For example, the light source **310a** may have the same configuration as the plasma light source **100** described with reference to FIGS. **1A** and **1B**, instead of a short arc discharge lamp. More specifically, the light source **310a** may include a pulse laser generator **110**, a CW laser generator **120**, a chamber **130**, a first dichroic mirror **140**, a second dichroic mirror **150a**, a first input optical system **170**, a second input optical system **180**, and a reflection structure **320**.

A pulse laser beam (e.g., visible ray pulse laser beam) from the pulse laser generator **110** may be input to the chamber **130** and ignite plasma. A CW laser beam (e.g., IR CW laser beam) from the CW laser generator **120** may be input to the chamber **130**, maintain the plasma in an ignited state, and increase the intensity of plasma. Plasma light (e.g., UV rays) discharged from the chamber **130** may be reflected toward the second dichroic mirror **150a** by the reflection structure **320** and be reflected toward a homogenizer **340** by the second dichroic mirror **150a**. Subsequent traveling processes of the output light may be substantially the same as those described above with reference to FIG. **16**.

Since the inspection apparatus **2000a** according to the present example embodiment includes the plasma light source **310a** having an electrodeless chamber structure and employs the reflection structure **320**, it is possible to simplify the light source structure, improve the brightness of light, and homogenize the light intensity distribution in terms of angle.

In the inspection apparatus **2000a** according to the present example embodiment, the plasma light source **100** of FIGS. **1A** and **1B** is used as the light source **310a**, but any one of the plasma light sources **100a** to **100f** of FIGS. **3** to **8** may be used instead of the light source **100** of FIG. **1A**. In addition, in the inspection apparatus **2000a** according to the present example embodiment, the light source **310a** is not limited to the plasma light sources **100** and **100a** to **100f** of FIGS. **1A** to **8**. For example, in the inspection apparatus **2000a** according to the example embodiment, examples of the light source **310a** may include a plasma light source using various ignition sources, such as microwaves, UV rays, high-frequency waves, a flash lamp, or a pulse lamp. In addition, the light source **310a** is not limited to a plasma light source and may be an LED light source or a laser light source.

In addition, in the inspection apparatus **2000a** according to the present example embodiment, a beam splitter **360** may be disposed between a homogenizer **340** and the collimation lens **352** as in the inspection apparatus **1000b** of FIG. **14**. In addition, as in the inspection apparatus **1000a** of FIG. **13**, the inspection apparatus **2000a** according to the present example embodiment may improve spatial arrangement utilization of elements by employing the mirror **270**.

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Referring to FIG. **23**, the inspection apparatus **2000b** according to the present example embodiment differs from the inspection apparatus **2000** of FIG. **16** in that an ND filter **330** is further included. For example, the inspection apparatus **2000b** according to the present example embodiment may further include the ND filter **330** above the homogenizer **340**. As such, since the inspection apparatus **2000b** according to the present example embodiment further includes the ND filter **330**, light intensity distribution may become more uniform in terms of angle.

For example, as can be seen from the graph of FIG. **21B**, the intensity of light is gradually weaker as a distance increases from the re-reflection area of the elliptical mirror **322** and the inner area where no re-reflection occurs toward the outer peripheral area. Although the change in the intensity of light is slight, the light intensity distribution may be non-uniform in terms of angle. Therefore, by employing the ND filter **330**, the inspection apparatus **2000b** according to the present example embodiment may further homogenize the light intensity distribution in terms of angle.

In addition, in the inspection apparatus **2000b** according to the present example embodiment, a beam splitter **360** may be disposed between a homogenizer **340** and a collimation lens **352**, as in the inspection apparatus **1000b** of FIG. **14**. In addition, as in the inspection apparatus **1000a** of FIG. **13**, the inspection apparatus **2000b** according to the present example embodiment may improve spatial arrangement utilization of elements by employing the mirror **270**.

Referring to FIG. **24**, the inspection apparatus **2000c** according to the present example embodiment differs from the inspection apparatus **2000a** of FIG. **22** in that an ND filter **330** is further included. Specifically, the inspection apparatus **2000c** according to the present example embodiment may employ the structure of the plasma light source **100** of FIGS. **1A** and **1B** as the light source **310a** and further include the ND filter **330** above a homogenizer **340**.

Since the inspection apparatus **2000c** according to the present example embodiment includes the plasma light source **310a** having an electrodeless chamber structure and employs a reflection structure **320** and the ND filter **330**, it is possible to simplify the light source structure, improve the brightness of light, and further homogenize the light intensity distribution in terms of angle.

In the inspection apparatus **2000c** according to the present example embodiment, the light source **310a** may be any one of the plasma light sources **100a** to **100f** of FIGS. **1A** to **8**. In the inspection apparatus **2000c** according to the example embodiment, the light source **310a** is not limited to the plasma light sources **100** and **100a** to **100f** of FIGS. **1A** to **8** and may employ various plasma light sources as described above. In addition, the light source **310a** is not limited to a plasma light source and may be an LED light source or a laser light source.

In the inspection apparatus **2000c** according to the present example embodiment, the beam splitter **360** may be disposed between the homogenizer **340** and the collimation lens **352**, as in the inspection apparatus **1000b** of FIG. **14**. In addition, as in the inspection apparatus **1000a** of FIG. **13**, the inspection apparatus **2000b** according to the present example embodiment may improve spatial arrangement utilization of elements by employing the mirror **270**.

While the inventive concept has been particularly shown and described with reference to example embodiments thereof, it will be understood that various changes in form and details may be made therein without departing from the spirit and scope of the following claims.

What is claimed is:

1. A plasma light source comprising:
 - a pulse laser generator configured to generate a pulse laser beam;
 - a continuous wave (CW) laser generator configured to generate an infrared ray (IR) CW laser beam;
 - a first dichroic mirror configured to selectively transmit or reflect the pulse laser beam and to selectively reflect or transmit the IR CW laser beam;
 - a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and to discharge plasma light generated by the plasma; and
 - a second dichroic mirror configured to transmit the pulse laser beam and the IR CW laser beam and reflect the plasma light, wherein the pulse laser beam is a ring-shaped beam and is input to the first dichroic mirror.
2. The plasma light source of claim 1, wherein the chamber has no electrodes therein.
3. The plasma light source of claim 1, wherein the chamber is surrounded by an elliptical mirror and is disposed at a focus of the elliptical mirror, and
 - the pulse laser beam and the IR CW laser beam are concentrated on the chamber by the elliptical mirror.
4. The plasma light source of claim 1, wherein the first dichroic mirror and the second dichroic mirror are disposed on a same axis to selectively reflect or transmit light according to a wavelength, so that input light beams incident on the chamber are synthesized and an output light beam from the chamber is separated from the input light beams.
5. The plasma light source of claim 1, wherein the pulse laser beam is input to the chamber by reflection of the first dichroic mirror and transmission of the second dichroic mirror, and
 - the IR CW laser beam passes through the first dichroic mirror and the second dichroic mirror and is input to the chamber.
6. A plasma light source comprising:
 - a pulse laser generator configured to generate a pulse laser beam;
 - a continuous wave (CW) laser generator configured to generate an infrared ray (IR) CW laser beam;
 - a first dichroic mirror configured to selectively transmit or reflect the pulse laser beam and to selectively reflect or transmit the IR CW laser beam;
 - a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and to discharge plasma light generated by the plasma; and
 - a second dichroic mirror configured to transmit the pulse laser beam and the IR CW laser beam and reflect the plasma light,
 wherein the pulse laser beam is input to the chamber by reflection of the first dichroic mirror and transmission of the second dichroic mirror,
 - the IR CW laser beam passes through the first dichroic mirror and the second dichroic mirror and is input to the chamber,
 - a concave lens is disposed between the pulse laser generator and the first dichroic mirror, and
 - a cylindrical lens is disposed between the CW laser generator and the first dichroic mirror.
7. An inspection apparatus comprising:
 - a plasma light source including:
 - a first dichroic mirror configured to transmit or reflect a pulse laser beam and reflect or transmit an infrared ray (IR) continuous wave (CW) laser beam;

- a chamber configured to receive the pulse laser beam to ignite plasma and the IR CW laser beam to maintain the plasma in an ignited state, and discharge plasma light generated by the plasma; and
 - a second dichroic mirror configured to transmit or reflect the pulse laser beam and the IR CW laser beam and reflect the plasma light, wherein the pulse laser beam is a ring-shaped beam and is input to the first dichroic mirror;
 - a first optical system configured to transfer the plasma light to an inspection object; and
 - a second optical system comprising an optical detector configured to detect light reflected from the inspection object.
8. The inspection apparatus of claim 7, wherein the chamber is surrounded by an elliptical mirror and is disposed at a focus of the elliptical mirror,
 - the pulse laser beam and the IR CW laser beam are concentrated on the chamber by the elliptical mirror, and
 - the first dichroic mirror and the second dichroic mirror reflect or transmit light according to a wavelength, so that input light beams incident on the chamber are synthesized and an output light beam from the chamber is separated from the input light beams.
 9. The inspection apparatus of claim 7, wherein the chamber has no electrodes therein.
 10. The inspection apparatus of claim 9, further comprising a uniformizing device including a neutral density (ND) filter disposed between the plasma light source and the first optical system and configured to gradually reduce a transmittance of the plasma light toward a central area of a cross section perpendicular to a traveling direction of the plasma light.
 11. The inspection apparatus of claim 10, wherein the uniformizing device is a reflection structure that includes a combination of an elliptical mirror and a spherical mirror and reflects the plasma light in one direction,
 - the elliptical mirror has a structure that is opened in a direction of a homogenizer, the spherical mirror is opened in a first direction and a second direction, the first direction being directed toward the elliptical mirror and the second direction being directed toward the homogenizer, and
 - the reflection structure is configured such that an opened portion of the spherical mirror in the first direction is coupled to an opened portion of the elliptical mirror.
 12. The inspection apparatus of claim 11, wherein the spherical mirror is configured to reflect the plasma light, which is not reflected by the elliptical mirror, toward the elliptical mirror, and
 - the spherical mirror is configured to homogenize an intensity of the plasma light in the central area and the intensity of the plasma light in an outer peripheral area on a cross section perpendicular to the traveling direction of the plasma light.
 13. The inspection apparatus of claim 7, further comprising:
 - a uniformizing device including a reflection structure that includes a combination of an elliptical mirror and a spherical mirror and reflects the plasma light in one direction; and
 - a neutral density (ND) filter disposed between the reflection structure and the first optical system and configured to gradually reduce the transmittance of the

plasma light toward a central area of a cross section perpendicular to a traveling direction of the plasma light.

14. The inspection apparatus of claim 7, wherein the first optical system includes:

- a collimation lens configured to collimate light output from a homogenizer into parallel light; and
- an objective lens configured to irradiate the parallel light on the inspection object and receive light reflected from the inspection object, and

the inspection apparatus further comprises a beam splitter disposed between the collimation lens and the objective lens or between the homogenizer and the collimation lens to split the light irradiated on the inspection object and the light reflected from the inspection object.

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